Master Thesis
Computer Science
Thesis no: MCS-2008:37
December 2008

Methods of analyses, providing and differentiation schemes Quality of Service in Optical Packet/Burst Switched Networks

Anna Maria Kaczmarek

Department of
Interaction and System Design
School of Engineering
Blekinge Institute of Technology
Box 520
SE – 372 25 Ronneby
Sweden

This thesis is submitted to the Department of Interaction and System Design, School of Engineering at Blekinge Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Computer Science. The thesis is equivalent to XXX weeks of full time studies.

Contact Information:
Author:
Anna Maria Kaczmarek
Address: ul. Sklodowskiej 3/18 49-300 Brzeg, Poland
E-mail: annie_k@wp.pl

University advisors:
Mia Persson
School of Engineering
Blekinge Institute of Technology, Sweden

External advisor(s):
Adam Grzech
Institute of Information Science and Engineering
Wrocław University of Technology, Poland

School of Engineering
Blekinge Institute of Technology
Box 520
SE – 372 25 Ronneby
Sweden

Internet : www.bth.se/tek
Phone : +46 457 38 50 00
Fax : + 46 457 102 45

ABSTRACT

In the last decade Internet has experience an explosive growth due to numbers of new users as well as their expectations to quality of receiving services. Those changes are major problem in core networks and the technology used so far does not assure satisfying results. The optical network has emerged as a promising technology to fulfill growing demands on networks capacity and performance. In last two decades wide ranges of the technologies of fiber communication and networking are focus of research in telecommunication domain. Optical Packet/Burst Switching Network (OPS/OBS) is a promising technology for future core networks due to good network utilization and adaptability to changes in the network infrastructure. Moreover OPS/OBS networks would be a good solution for an increasing numbers of real-time and interactive Internet applications. This problem forces development of Quality of Service (QoS) mechanisms and technologies. The idea of providing QoS in All-Optical Networks brings nonnegotiable opportunities. However, due to some nowadays technology limitation most aspects exist only in theory. Nevertheless research in area of both modeling and providing QoS in All-Optical Networks could give the strong fundaments for implementing this mechanisms when the nowadays technology will be able to bring it to reality.

This thesis presents the idea of providing QoS in All-Optical Networks. The thesis investigates available mechanisms of differentiation services in Optical Packet/Burst Networks. It provides an overview of current state-of-art in this domain together with literature research in order to evaluate and present qualitative and quantitative comparison of three chosen algorithms which are suitable for providing QoS in OPS/OBS networks. The thesis includes also research in teletraffic modeling of Optical Networks.

CONTENTS

ABSTRACT 1
CONTENTS 2
LIST OF ACRONYMS 4
INTRODUCTION 5
BACKGROUND 5
RESEARCH AIM AND OBJECTIVES 7
RESEARCH QUESTION 7
THESIS OUTLINE 7
CHAPTER 1: OPTICAL NETWORKS 9
1.1 NETWORK CLASSIFICATION. 9
1.2 OPTICAL NETWORKS 10
1.3 ALL-OPTICAL NETWORK ARCHITECTURES 11
1.3.1 Wavelength Routed Optical Networks (WRON) 12
1.3.2 Optical Packet/Burst Switching Network 12
CHAPTER 2: QUALITY OF SERVICE METRICS 14
2.1 QOS PARAMETERS 14
2.2 PACKET LOSS RATIO 15
2.3 QOS FRAMEWORKS 15
2.3.1 Integrated services 15
2.3.2 Differentiated Services 15
CHAPTER 3: MODELING OPTICAL NETWORKS 17
3.1 COMBATING PACKET LOSS IN OPS/OBS NETWORKS 17
3.1.1 Contention resolution 17
3.1.2 Intelligent packet loss combating mechanisms: 18
3.2 TELETRAFFIC ANALYSIS OF OPS/OBS NETWORKS 18
3.2.1 OPS/OBS node synchronization 18
3.2.2 Network models 18
3.2.3 Arrival models 19
3.3 QUALITY OF SERVICE DIFFERENTIATION SCHEMES IN OPS/OBS 19
3.3.1 Dropping based QoS differentiation scheme 19
3.3.2 QoS differentiation schemes based on access-restriction 20
3.3.3 QoS differentiation schemes based on preemption 21
CHAPTER 4: METHODOLOGY 22
CHAPTER 5:QOS DIFFERENTIATION SCHEMES AND ALGORITHM FOR OPS/OBS NETWORKS 24
5.1 MAIN TASK FORMULATION 24
5.1.1 Task of providing QoS in OPS/OBS networks 24
5.1.2 Comparison of the task of providing QoS in optical networks and analogous task in wire and wireless networks. 25
5.2 SYSTEM MODEL 26
5.2.1 Switch architecture 26
5.2.2 General traffic model 27
5.3 QOS DIFFERENTIATION SCHEMES AND ALGORITHMS. 29
5.3.1 The Wavelength Allocation algorithm 29
5.3.2 The Preemptive Drop Policy algorithm. 31
5.3.3 Dropping based QoS differentiation scheme 34

CHAPTER 6: SIMULATIONS OF ALGORITHM PROVIDING QOS DIFFERENTIATION IN OBS/OPS NETWORKS 37
6.1 SIMULATOR 37
6.2 ALGORITHM'S ANALYSIS 37
6.2.1 System model 38
6.2.2 The Wavelength Allocation algorithm 38
6.2.3 The Preemptive Drop Policy algorithm 40
6.2.4 The Intentional packet dropping algorithm 41
6.3 COMPARISON OF THE PRESENTED SCHEMA 41
CHAPTER 7: SUMMARY 42
7.1 HYPOTHESIS EVALUATION 43
7.2 CONCLUSIONS 43
7.3 FURTHER WORK 45
REFERENCES 46
APPENDIX A 50

LIST OF ACRONYMS

AQM	Active Queue Management
AR	Access Restriction
BE	Best Effort
DiffServ	Differentiated Services
D-WRON	Dynamic Wavelength Routed Optical Networks
E/O	Electrical-to-Optical
FDL	Fibre Delay Line
FOWC	Full Output Wavelength Converter
Gbps	Gigabit per second
HP	High Priority
IF	Input Fibre
IntServ	Integrated Services
IPD	Intentional Packet Dropping
IW	Input Wavelength
IWL	Input Wavelength
Kbps	Kilobit per second
LCC	Lost Calls Cleared
LP	Low Priority
Mbps	Megabit per second
O/E	Optical-to-Electrical
OBS	Optical Burst Switching
OF	Output Fibre
OPS	Optical Packet Switching
OT	Offset Time
OW	Output Wavelength
PCT-I	Pure Chance Traffic Type I
PCT-II	Pure Chance Traffic Type II
PDP	Preemptive Drop Policy
PLR	Packet Loss Rate
QoS	Quality of Service
RAM	Random Access Memory
TAG	Tell-And-Go
TAW	Tell-And-Wait
Tbps	Terabit per second
WA	Wavelength Allocation algorithm
WDM	Wavelength Division Multiplexing
WRON	Wavelength Routed Optical Networks

Background

In the last decade Internet has experienced an explosive growth due to numbers of new users as well as growing popularity of Internet and increasing access network capacity [Per02]. Internet offers attractions to users, such as forums, e-books or online games all over the world. Moreover, it is valuable source of information in many domains like politics or science. Nowadays Internet becomes also very useful tool in business or medicine. For instance it enables to perform teleconference between doctors during surgery, even if they are very far from each other. Constant development of different kind of companies imposes on the need of better communication between theirs parts. To attract customers Internet Service Providers (ISP) offer faster, cheaper and safer services. However, the more people use Internet the more data needs to be transmitted and the requirement for network ability to handle it increases. Moreover, for some services like real-time video or telemedicine network should transmit the data fast enough without losing any part. The major problem in core networks is to achieve balance between costs and providing satisfies services.

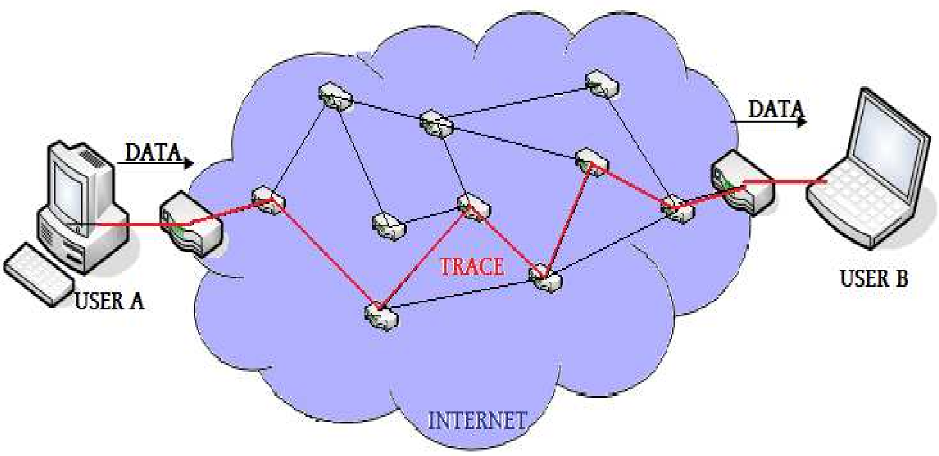


Figure 1. Data transmission from one point to another over the Internet

Figure 1 presents how data can be transmitted from one point to another over the Internet. In switching point the router or switching device decides where should transmit the data according to some implemented algorithms. The decision about the path is taking depending on accurate situation in the network. The number of users and data transmission impose on the state of network. Moreover some data need to be transmitted without losing any part. The switching devices should take decisions aiming at minimizing the loss ratio, time of transmission and maximizing the widely understand quality of communication.

One of the proposed solution to problem of growing requirements for network speed or capacity is Wavelength Division Multiplexing (WDM) technology. This method allows building several channels - wavelengths to transmit data in single optical fiber, which is a waveguide for light. However, WDM is utilized in point-to-point architecture [Øve06a] with electronic switches. This means that the transmission is fast between the switching points, but after reaching them it must be converted to electronic signal in order to make the decision, where it should be send next. Before leaving switching device the signal is converted to optical one. This conversions called O/E and E/O waste a lot of time, especially while considering speed between the double conversions. The solution of using all-optical networks seems to be promising technology. On the other hand, networking in optical domain is quite new technology and it gives many areas for research.

Another issue to concern in today's networks is satisfying high demand of some group of users. Nowadays Internet provide only the best-effort services, where packets are threaded equally and transmitted in the best possible way according to available resources. "For the services like email and file transfer applications best effort services may be sufficient, hence real-time video, interactive gaming and telemedicine are more demanding" [Ram06]. This problem forces development of Quality of Service (QoS) technologies. Those technologies mainly concern the classification of generated traffic or flow in order to enable providing services for distinguished classes of users.

Optical network which provide QoS seems to be a promising technology to fulfill all mentioned before requirements, especially while considering the future possible needs speed. It is very actual problem and many investigations are being made in this domain. This thesis focuses on two optical technologies Optical Packet Switching (OPS) and Optical Burst Switching (OBS). Some issues have been resolved in this area of interest, such all-optical wavelength conversion [Dur96] and all-optical processing. However there are still challenges like combating packet due to contention or supporting QoS differentiation. This thesis addresses one of the major problem in OPS/OBS networks: providing QoS differentiation schemes. Major challenge in OPS/OBS is to provide accurate analytical models for network layer related issues [Rob01]. Moreover, there is a lack of models that capture the effects of QoS differentiation.

Research aim and objectives

This thesis investigates the methods of analysis, evaluation and providing Quality of Service suitably for Optical Burst Switched Networks. All-optical networks have some seriously limitations, such as packet buffering in switching devices. However, it also offers great features like fulfilling the growing requirements for real-time application. One of the area of interest in the research concerning all-optical networks focuses on providing quality of service. This thesis focuses on performing differentiation schemes and algorithm that will allow providing quality of service guarantees. The main purpose of this work is to perform analysis if and on which level presented differentiation schema and used algorithms meet the QoS requirements. Existing differentiation techniques are investigated and compared in order to obtain best suiting methods. To achieve the goal following research objectives are realized:

- Perform an overview of optical network architecture and discuss the impact of specified features of these networks.
- Formulate the task of providing QoS in Optical Networks including comparison to analogical problem in wire and wireless network.
- Prepare description of differentiation schemes of providing QoS in Optical Networks.
- Perform simulation research and elaborate result of quantitative research.
- Compare the differentiation schemes based on analytical and simulation results.

Research questions

The main goal of presented study is to evaluate the hypothesis. However the research process includes also some sub questions.

Hypothesis: Which differentiation schemes suits best for providing QoS in Optical Networks?

Research Question 1: What are the main differences while implementing QoS in optical networks compared to the wire and wireless networks?

Research Question 2: Which algorithm based on differentiation scheme gives the best results according to the packet loss ratio?

Thesis outline

This thesis is organized as follows:

Introduction presents the background and research objectives as well as the thesis limitation.

Chapter 1 presents the history of fibre-based communication, Optical Network classification and introduces the features of Optical Packet Switch/Burst Networks..

Chapter 2 introduces the idea of providing Quality of Service in networks and the general overview of different QoS approach.

Chapter 3 discusses issues related with modeling Optical Networks and implementing Quality of Service, the limitation as well as the opportunities of fiber-based networking.

Chapter 4 presents methodology, which was used in order to achieve the main goal of this study.

Chapter 5 introduces the main purpose of this work by formal task formulation. Here we also present the analysis of differentiation schemes based on teletraffic theory.

Chapter 6 presents the simulation process and achieved results.

Chapter 7 gives the summary of performed work and answers for research question.. Here we discuss the hypothesis evaluation as well as the possible ways to develop this thesis.

CHAPTER 1

OPTICAL NETWORKS

The term network addresses interconnection between systems in group, which shares information. Telecommunication network refers to architecture, which consist of nodes and links between them. This architecture with implemented methods allows transmitting data from one node to another. Major issue in networking is to provide services, which allow transmitting data safely, fast and in most optimal way. To make transmission safe many security mechanisms are use to protect data against unauthorized access. For optimal transmission stands methods of routing, the process which on the basis of network state selects paths along which the data are transmitted.

1.1 Network classification.

The nowadays' network can be divided into several different classes basis on some characteristic attributes. The major division is shown on the Figure 1.1

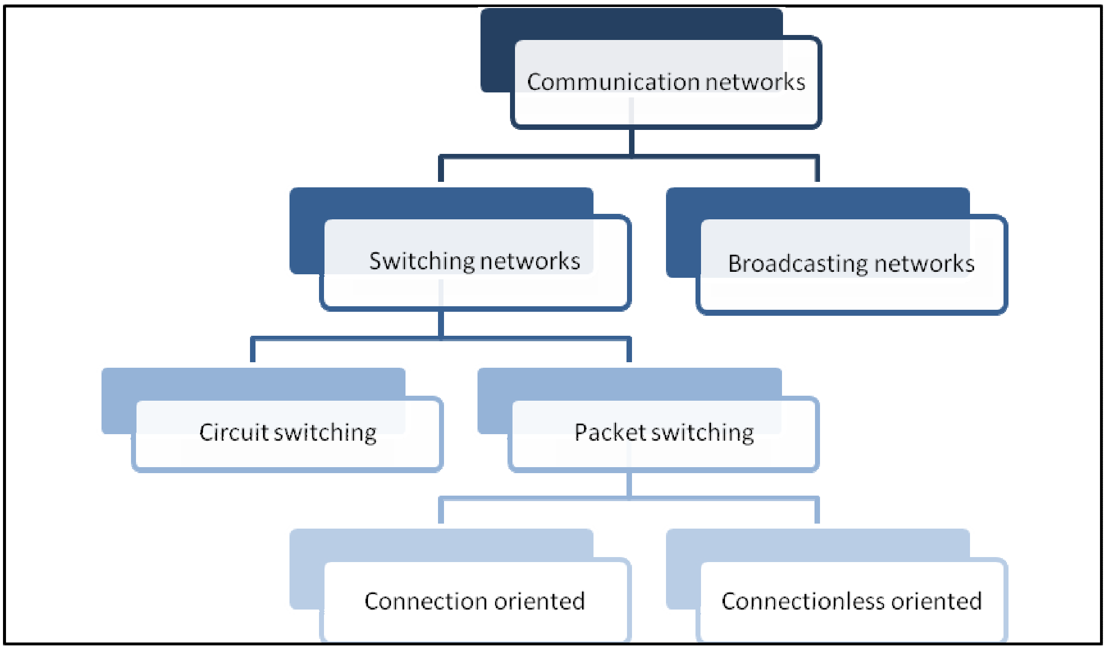


Figure 1.1 Network classification based on type of sending the data

The first division of telecommunication networks basis on the way in which data are send. In broadcasting networks the information is send from one node to all nodes in network. The good example of this kind of network is radio, satellite or Ethernet. The idea of switching is to transfer the information between dedicated nodes in the network. Depending on the strategy of transferring we can distinguish two types of switching networks:

Circuit switching, when before the transmission the channel is being established and all necessary resources to service the connection are reserved. Second approach is based on the strategy store-and-forward and no reservation of resources is being made before sending the data.

Moreover the network traffic can be divided into two classes:

- the traffic sensitive to delay. Generally this kind of traffic is observed in circuit-switched network.
- traffic sensitive to loss.

Based on this division all application that are served in the network and the traffic which is generated by network's applications can be also divided into two classes:

- application real-time sensitive
- application delay tolerant.

It should be also mentioned that depending on requirements and purpose for the network different kind of network types can be used. Nevertheless, independently from this classification and attributes of each type of network, the major problem in nowadays telecommunication is time and size of sending information, which gives the requirement for higher speed of the network. To solve this issue the technology turn to the opportunity, which is given by optical networking.

1.2 Optical Networks

The idea of optical networking aroused in the early 1980s, when fiber–optic cable was invented, which permits to transmit number of data over long distances. Fiber-optic communication is a technique, in which information is carried by electromagnetic wave (electromagnetic carrier wave).

According to [Opt07] "optical networks are high-capacity telecommunication network based on optical technologies and components that provide routing, grooming and restoration at the wavelength level as well as wavelength-based services". Traffic grooming in optical networking is optimization process of grouping different traffic streams into higher speed streams.[Wan 01]. Restoration term is used to describe the process by which the communication path is established between nodes after disruption of the original one.

Optical networks development can be divided into three stages (generation), as can be seen on figure 2. The first step towards optical networking was the

Wavelength Division Multiplexing (WDM) technology. The second and third generations correspond to all-optical networks, where all transmitting processes are implemented in optical domain.

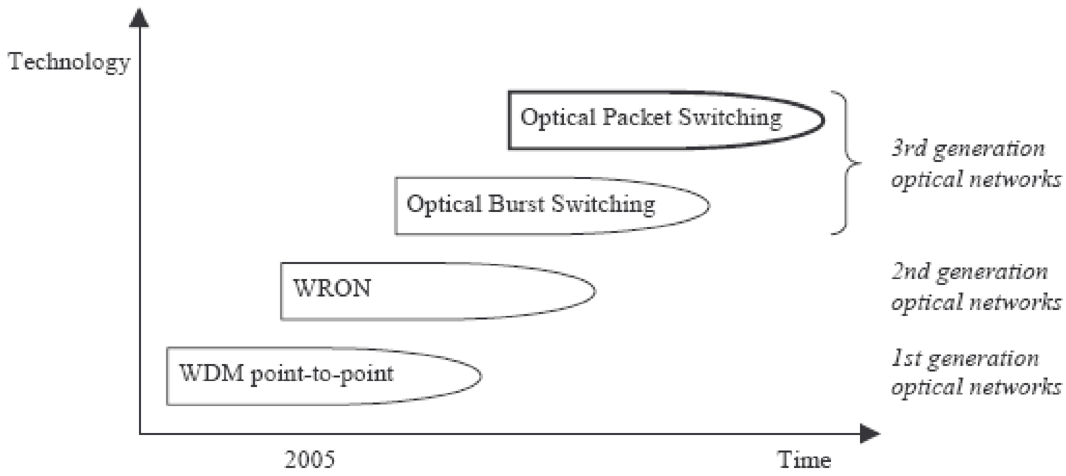


Figure 1.2 Evolution of photonic transport network [Øve05a]

Wavelength Division Multiplexing (WDM)

WDM technology allows combine multiply optical carrier (OC) signals into one signal on a single optical fiber by using different wavelengths. OC is a term used to specify a speed of fiber-optic network. As the light is an electromagnetic wave, each wavelength is equal to the color of light and each of wavelength can carried some information. Nowadays WDM is used in point-to-point architectures [LN 01], which means that the optical-electrical and electrical-optical conversions in each switching point are needed. The costs of switching as well as limits of electronic switches cause development of all-optical architecture solutions, which provide more cost efficiently network transport services and higher data transparency.

1.3 All-optical network architectures

"All-optical network consists from optical fiber links between nodes with all-optical switching and routing of signals at the nodes, without electronic regeneration" [Ram02]. Providing switching and routing mechanisms at the optical layer in the second and third generation of photonic transport network obviate the need for conversions to the electronic domain. Comparing to standard model of networks layer like ISO/OSI [Tan04] or SONET [Son08] the all optical network architecture provide very simple layer model, which can be seen in figure 1.2 [Jaj01]

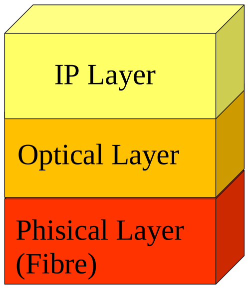


Figure 1.3 All-optical network architecture.[Jaj01]

1.3.1 Wavelength Routed Optical Networks (WRON)

The second generation is Wavelength Routed Optical Networks (WRON), where all-optical connections, are established between edge nodes in the optical core network [Ram02] before the data transmission. "A core network is a backbone network, usually with a mesh topology, that provides any-to-any connections among devices on the network" [Lin08]. This connections named lightpaths can be wavelength converted at intermediate nodes (optical wavelength converter), but the whole path between edge nodes is reserved and can be released only when the transmission ends. However, the wave channels have a very large granulation and the occupying a single channel by a small set of data is very ineffective.

1.3.2 Optical Packet/Burst Switching Network

As the WRON technology seemed to be non-optimal due to resources utilization [Zan00] the most promising all-optical network technology is Optical Packet Switching (OPS) and Optical Burst Switching (OBS). Both technologies are included into third generation optical networks

1.3.2.1 Optical Packet Switching

OPS network basis on the idea that packet should be entirely processed, forwarded and buffered in optical domain. OPS works similarly to packet switching already implemented in electronics [Yao00]. The idea of packet switching is to transmit data as discrete blocks of information. Packets are put into optical packet payload and routed together with control information between nodes in network. This means that the payload must be delayed in Fiber Delay Lines (FDLs) at the switch while setup is performed [Und04]. There is distinguishing into two modes in which OPS network can operate: asynchronous, where packets arrive at a switching device at non-deterministic instants, what mean that there doesn't exist defined time moments. In second mode: synchronous packets arrive at an optical core switch in synchronized and equally spaced time slots. [Nor03].

1.3.2.2 Optical Burst Switching

The idea of this technology is to aggregate incoming packets from the access network into bursts of defined size. When the burst is ready according to timer or size it is sent into network. OBS uses out-of-band control information, where the burst transmission is preceded by control packet. Important issue is to perform optimal scheduling schemes. Those schemes for OBS were proposed and described in [Xu 01]. The most promising schedulers are Tell-And-Wait(TAW) and Tell-And-Go (TAG). In the first case prepared burst waits for control packet report about resource reservation, and is sent after confirmation of enough available resources comes. In Tell-And-Go schemes burst is sent right after the control packet and the reservation is being made during the transmission. The role of control packet is to reserve necessary resources for the burst. Another scheduling scheme is Just Enough Time model, where burst is sent after control packet after defined period of time (named Offset Time).

CHAPTER 2

QUALITY OF SERVICE METRICS

Quality of Services in networks concern traffic or flow classification in order to treat them in specific way according to class they represent. Qualities of Services allow differing traffic class and providing services to that class. [Grz02] In general QoS is the network ability to guarantee providing services for specified traffic class. Availability of providing different services for specified traffic class require implementation in the network suitably mechanisms of differentiation, identification and management of all traffic class and network's elements. Differentiation mechanism focus on rules of admission control and resource allocation, as well as number of resources allocated to the users. The basis conception is, as mention before, providing best-effort services. When talking about QoS in networks a several approaches to this case should be considered.

As mention before, we can distinguish two classes of traffic: circuit switched and packet switched. Based on these division two major classes of QoS metrics were introduced:

- Call control parameters. This class is dedicated to circuit switched networks as well as connection-oriented. All parameters in this set are related to connection attributes, such as setup, release and connection acceptance.
- Information Transfer Parameters, which are suitable in various type of networks independently from the way of providing resources, which mean they characterize packet switching as well as circuit switching networks. Parameters that belong to this metric class are detail described in next paragraph.

2.1 QoS parameters

While introducing the QoS parameters included in transfer class, it should be mention that elements in this group is strictly reliant from the application type, that is being served, meaning they are dependent on traffic type or application sensitivity. In order to define set of parameters suitably for transfer quality characterization the main issues should be considered. Firstly, parameters should be fitted to the application and measure attribute that are required, depending from the class application belongs. They also should be award of all the mechanisms used in the network, as well as the scale on which they describe quality. For instance if voice transmission is being considered, the loss ratio parameter will not be an adequate parameter to characterize quality, while delay time describes properly application delay sensitive. For purpose of this thesis we describe Packet Loss Ratio, as it was define the crucial parameter for theoretical and empirical study presented in this work. The detailed description of all parameters can be found in [Grz02].

2.2 Packet Loss Ratio

Packet Loss Ratio is defined as the average of relation the lost data to all data send by the source [Grz02]. This quality metric has different implementation and is depended on network architecture. This dependence will be shown in main task formulation. In optical networks packet can be lost due to several reason. One of the cause is contention resolution issue. Contention occurs when packet/burst is destined to an output wavelength that is currently transmitting or when at least two packets/bursts are destined for the same output wavelength in the same time-slot. The mechanism and proposed solution will be introduced in next chapter. Implementing QoS differentiation schemes in optical networks has also influence on PLR since the proposed algorithms decide which packet/burst should be processed.

2.3 QoS frameworks

Providing QoS that fulfills different applications' requirements distinguish two major frameworks: integrated services (IntServ) and Differentiated Services (DiffServ).

2.3.1 Integrated services

IntServ [Bra94] is a per-flow based QoS framework with dynamic resource reservation. The idea of integrated services base on assumption, that quality of service is guarantee by resource reservation for each generated flow. Reservation is establishing network route before transfer starts. According to [Grz02] IntServ distinguish two models. First model is Guaranteed Service (GS) with providing defined resources allocation and upper bound delay. GS ensure that no packet will be lost and bound maximal delay value. Controlled Load Service is second model of IntServ. CLS is resource reservation based on average values of the traffic parameters without delay value guarantee.

2.3.2 Differentiated Services

DiffServ [Bla98] is a per-aggregate-class based service discrimination framework using packet tagging. Packet tagging uses bits in the packet header to put down a packet to class with special treatment. Main assumption of differentiated services is that different qualities of service can be provided using small numbers forwarding class or behavior aggregate. Resource allocation is made by limitation of introduced traffic. QoS can be described qualitatively (relative) or quantitatively (absolute) [Zha01]. In absolute definition QoS is guaranteed to an individual flows or traffic classification, which basis on rules called Service Level Agreement (SLA). SLA is a contract between user and provider, which define number of forwarding class, level of service and bound to the values of network metrics (such as delay or loss) for the high priority class. The absolute QoS model provides worst-case guarantee based on the loss, delay, and bandwidth to applications. This type of hard guarantee is essential for the classes of delay and loss sensitive applications, which include multimedia and mission-critical applications [Zha03b]. Relative QoS definitions relate the treatment received by a class of packets to some other class of packets. According to [Øve05a] relative guarantees can further be divided into qualitative guarantees, where the QoS parameters of the various classes are qualitatively ordered and proportional guarantees, where QoS parameters of a certain class are given quantitatively relative to another class.

The most significant QoS parameters in the context of optical networking are: delay, delay-jitter, packet loss ratio (PRL) and throughput.

According to paragraph 1.3 all-optical networks have some obviously boundaries that make it impossible to used algorithms or solutions already applied in point-o-point WDM with electronic switches. This is because of existing QoS schemes differentiated traffic between the service classes basing on traffic management algorithms. For instance traffic with lower priority is buffered until traffic with higher priority is processed. An example can be seen in [Wyd02] or [Cri03], where Active Queue Management (AQM) algorithms were described. In optical network buffering is available only through Fiber Delayed Lines (FDLs), "where packets are delayed by being transmitted on a fixed length optical fiber" [Øve06b]. However, this solution does not replace random access memory (RAM), which is essential to perform traffic management. One of the reasons is that, the FDLs can only delayed packets for a limited amount of time. Nevertheless, the benefits of using OPS/OBS network are enough significant to research for providing QoS without using electronic RAM.

CHAPTER 3

MODELING OPTICAL NETWORKS

Major challenge in OPS/OBS is to provide accurate analytical models for network layer related issues [Rob01]. Moreover, there is a lack of models that capture the effects of QoS differentiation. In this chapter the problem of providing QoS in OPS/OBS networks will be formulated and challenges

3.1 Combating packet loss in OPS/OBS networks

Very important issue, which strongly influences the QoS differentiation solutions, is contention resolution. According to [Yao03] packet loss at the network layer is a crucial issue due to contention. Contention occurs when packet/burst is destined to an output wavelength that is currently transmitting or when at least two packets/bursts are destined for the same output wavelength in the same time-slot. Both cases will cause dropping packet/burst and increasing packet loss rate (PLR). To avoid this situation appropriate mechanisms to combat such packet/burst loss are used.

Currently we can distinguish two main approaches to resolve the problem of combating packet/burst loss: contention resolution, based on reducing the average of packet loss when contention occurs, and intelligent packet loss combating mechanisms, which reduce PLR using intelligent network behavior.

3.1.1 Contention resolution

"Choice of contention resolution architecture highly influences the mode of operation of the QoS differentiation schemes". [Øve06b]. Generally contention resolution is deciding which device gains access to a resource first, when more than one wants to use it at the same time. The contention resolution mechanisms according to [Øve06b] can be grouped into three domains:

- **Wavelength domain**, where contending packets are converted to idle wavelengths on the same fiber using wavelength converters.
- **Time domain**, where contending packets are delayed and scheduled for transmission at a later point in time when the wavelength is available**.**

- **Space domain**, where contending packets are transmitted on the same wavelength on another idle output fiber, which leads to a node other than that originally intended.

More detailed methods can be found in [Lu 04] for Optical Packet Switch and in [Gau04] for Optical Burst Switched networks.

3.1.2 Intelligent packet loss combating mechanisms:

Second approach includes various methods, which are different from contention resolution, since they do not attempt to reduce the number of packets/bursts loss when contention occurs. One of these techniques is presented in [Maa04], where the PLR is continuously monitored and kept below an upper limit by utilizing an adaptive rate control algorithm. Other solution, the hop-based or merit-based priority scheme for reducing the overall network PLR has been examined in [Whi02d] [Kim02].

3.2 Teletraffic analysis of OPS/OBS networks

OPS/OBS networks are quickly developing technology. However, as it is still young research area of telecommunication domain, many issues are not introduced in reality. In this paragraph we present an overview of methods of modeling OPS/OBS network.

3.2.1 OPS/OBS node synchronization

As mentioned before OPS and OBS networks can work in either asynchronous or slotted transfer mode. In synchronous OPS network [Yao03] time is slotted and the packet switching occurs only at the beginning of time slot. All packets have the same size and the duration of single slot is equivalent both to the sum of the packet size and optical header length. Each packet that arrives and enters the switch must be aligned. In synchronous OBS both data and control channels are slotted. Moreover, the control channel consists from several Burst Header Packet (BHP) slot and data slot is the multiply number of data slot. In the asynchronous OPS/OBS networks packets or burst may arrive and enter the switch in any point of time. However, while packets can have different size, the beginning and end of data burst must be specified in time units [Laz07].

3.2.2 Network models

In recent years many Internet research were focused on traffic modeling in optical networks. The major feature of OBS and OPS networks is that they are modeled as loss system [Tur99]. “This is simplification of the reality, because queuing delay may occur in optical networks from e.g. FDLs “[Øve05a]. However, research study has shown that this generalization can be acceptable [Bjø02a] [Yoo00]. The major challenge is to provide precise analytical model of OPS/OBS network, which will be able to capture the effects of buffering, contention resolution or QoS differentiation. Unfortunately, the current state of development of OPS and

OBS technology still does not satisfy all requirements such as providing suitable contention resolution or QoS guarantees. [Laz07]. It is also important to underline that synchronization mode influences on traffic model. The asynchronous networks are modeled using “continuous-time Markov chains, while slotted networks are modeled using discrete-time Markov chains.

3.2.3 Arrival models

The different synchronization mode causes two different network models. Each of that architecture has several solutions for modeling the packet arrival process.

In [Øve04b] various Marcovian arrival models were presented for asynchronous OPS network, with detailed description of Erlang and Engset lost calls cleared (LCC) arrival models. Author proposed also Engset Asymmetric arrival model and the Engset Non-looping arrival model. One more Engset-based arrival model the Engset Overflow is delivered in [Øve05b]. The comparison of Poison and Binominal arrival models can be found in [Øve04c].

All analytical models base on stochastic processes and are widely used in performance modeling of OBS/OPS networks. Nevertheless, the choice of analytical model strongly influences on the evaluation of contention resolution mechanism and QoS differentiation schemes, as well as the investigated network parameters.

3.3 Quality of Service differentiation schemes in OPS/OBS

In this section most popular and suitably both for OPS and OBS network QoS differentiation schemes will be introduced. In order to ensure better understanding this issue two major challenges related to QoS differentiation mechanisms should be indicated.

The most important issue is high dependency between providing QoS differentiation by utilizing the WDM layer and used contention resolution architecture. Currently only a small subset of possible contention architectures has been considered for QoS differentiation and further research on the various types of QoS differentiation schemes for OPS and OBS is crucial. Another challenge is to offer absolute QoS, since most proposed solutions for QoS differentiation in OPS and OBS provide relative QoS guarantees.

According to the literature most of the differentiation schemes concert the Packet Loss Ratio (PRL) as a crucial quality parameter. These schemes can be based on preemption, access-restriction or intentional packet dropping.

3.3.1 Dropping based QoS differentiation scheme

Dropping based QoS differentiation scheme is suitable for both OBS and OPS and has been presented in [Che01]. With packet dropping, low-priority traffic is dropped with a certain probability before attempting to seize a resource. This model basis on the assumption that “the service differentiation of a particular QoS metric is proportional to the factors that a network service provider sets.” Equation (1) describes the proportional model for all pairs of services classes:

$$\frac{q_i}{q_j} = \frac{s_i}{s_j} \qquad (i, j = 0,1,..., N) \qquad (1)$$

where *i* is number one of N class, q_i represents QoS metric and s_i is the differentiation factor. With assumption that the class 0 has lowest priority, packets with lower priority is intentionally dropped when equation (1) is violated.

This scheme can be modified to provide absolute QoS in asynchronous OPS/OBS network, what was performed in [Zha03a]. Idea of proposed early drop scheme was to introduce probabilistic service differentiation technique where bursts from class with lower priority are intentionally dropped with defined probability, before possibly contending with the bursts from class with higher priority.

In both solutions PLR for low-priority traffic increases, but it significantly decreased for high-priority traffic.

3.3.2 QoS differentiation schemes based on access-restriction

This differentiation scheme is suitable both for asynchronous OPS and OBS network. The access restriction methods basis on the assumption, that a subset of the available resources is exclusively reserved for higher-priority traffic.

One of the proposed solutions is Wavelength Allocation algorithm (WA) [Øve06b]. Assume that the resources are represented by wavelengths converters. To each of the service level we assign different number of those converters. Some can be reserved for the highest priority traffic, while others are shared among all traffic. Each class arrivals is either accepted or dropped according to accessible converters and class priority.

In [Cri03] as a solution to this schema for both asynchronous bufferless OPS and asynchronous OPS with FDL buffers new method was introduced. The idea is to isolate service classes by employing access-restriction to input wavelength converters and buffers. Basically on this assumption Combined Wavelength Allocation and Threshold Dropping (WA/TD) technique was introduced. This is modification of described above WA algorithm. In WA/TD method each service class belongs to one of two levels of QoS. A further differentiation is achieved by adding threshold dropping in the buffer. When the buffer occupation is above the threshold, the packets from lower-priority class are discarded while the other packets are accepted until the buffer is full.

3.3.3 QoS differentiation schemes based on preemption

All preemptive techniques base on the assumption that all free resources are available to all traffic. “When all resources are taken, a high-priority packet may take over (preempt) a resource currently occupied by a low-priority packet, which is then lost” [Øve06b]. However low-priority packet cannot preempt any packet with higher priority. This solution results in lower Packet Loss Ratio (PRL), even when average value of given resources are available to high-priority packets. In Preemption Drop Policy method the packet with higher priority can be lost only when all wavelengths are occupied by packet with equal or higher priority.

CHAPTER 4

METHODOLOGY

The purpose of this study is to present qualitative and quantitative comparison of methods of analysis, evaluation and providing Quality of Service suitably for Optical Packet/Burst Switched Networks. The main task is to show and evaluate differentiation schemes that fulfill requirements of QoS. In order to ensure such results this study basis on common research methodology, that was used for example in [Øve05a]. Presented differentiation schema is evaluated in two ways, firstly using teletraffic analysis an analytical model is estimated, and at the same time a discrete simulations is being performed. The process of research includes several steps:

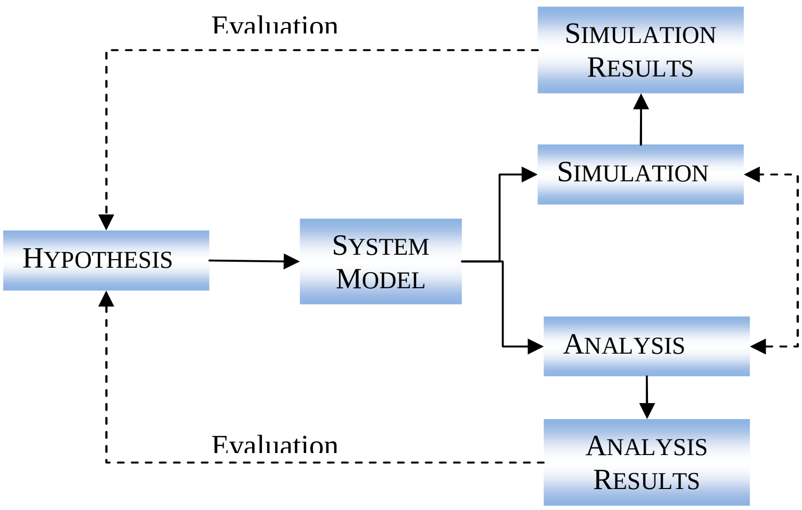


Figure 4.1 The methodology used in this thesis.

Hypothesis

As indicated before the main goal of this study is to perform comparison of QoS differentiation schemes. The main question of this work is “What is the most suitable QoS differentiation scheme according to the PLR?”. Based on this several solutions have been proposed and for each both analysis and simulation have been performed. For purpose of this work three approaches to the differentiation scheme has been evaluated. The main hypothesis includes subquestion as well. The algorithms presented in next chapters are evaluated both separately and together with each other. The individual analysis of those methods is being made with the object of qualifying whether the algorithm fulfill QoS differentiation requirements, or not.

System model

The system model design process has been made in way that provides all essential features of both the network architecture and differentiation scheme mechanisms. The construction basis on informal pictures and descriptions, which allow indicating all issues that have an impact on evaluating the hypothesis. This approach give the opportunity for better understanding the main problem as well as the necessity of using specific tools.

Examination method

In order to get more representative results the hypothesis is evaluated in two ways. All differentiation schemes are simultaneously evaluated using teletraffic analysis and performing simulations.

Analysis concern models build based on teletraffic theory. Those models can be found for example in [Gro74][Kle75][Kle76][Ive99]. Investigation the hypothesis with teletraffic analysis has some limitations due the complexity of analytical calculation, so some simplifications of the model has been assumed. Specifically, the aforementioned simplifications are as follows: analytical analyses basis on simplify traffic model, because obtain results for more complex model could be impossible. For analytical research we assume Engset Arrival Model. Furthermore we concern specific network architecture and switch model: an asynchronous optical packet switch with full wavelength conversion and no internal blocking, which is suitable both for Asynchronous OPS and OBS with Tell-And-Go Schedule scheme. This two main assumptions let us to limit the considerations and measure the traffic behavior on single output wavelength.

Based on the system model simulations are performed. For the simulations an application has been implemented: OpticalSwitchSimulation. This tool is dedicated to verify the statements which appeared in this work, as well as to address the need of presented model.

Results

Results from analysis and simulations are firstly use to validate the model and then to evaluate the hypothesis. The analytical evaluation is based on the same traffic family model. However in order to evaluate the hypothesis analytically and obtain proof some simplification were made. The simulation results includes two stages. First step verify the statements from analytical discussion, as well as allows us to prepare the proposed algorithms for stage two. Here, we obtain the best values of each algorithm parameters according to PLR. In second step comparison of algorithms is being performed, based on the results from stage one.

CHAPTER 5

QOS DIFFERENTIATION SCHEMES AND ALGORITHM FOR OPS/OBS NETWORKS

In previous chapters some very important issues in all-optical networks were introduced. Presented overview of the QoS differentiation schemes and methods of teletraffic modeling indicated many problems, which occur while performing network architecture. The main purpose of this study is to show qualitative and quantitative comparison of differentiation schemes providing Quality of Service in Optical Packet/Burst Switched Networks. In order to perform reliable simulation and get representative results we introduce analytical model of the network and QoS differentiation schemes suitably for OBS and OPS.

5.1 Main task formulation

In this paragraph we formulate task of providing QoS differentiation in OPS/OBS network. However, before introducing the main goal of this thesis, an introduction to providing service differentiation will be performed.

5.1.1 Task of providing QoS in OPS/OBS networks

The general task of providing differentiation QoS in optical network is formulated as follows: For given network architecture, arrival model find the algorithm of decision making in switching device to optimize chosen quality parameter. In presented study this problem is brought to perform comparison of algorithms based on chosen QoS differentiation schemes. As indicated before QoS can be considered basis on several parameters. The crucial quality parameter that was chosen to deliver qualitative and quantitative comparison of QoS differentiation schemes and algorithm is PLR. As will be shown in later chapter considering the PLR is the natural consequences of proposed switch and network architecture.

Table 1 presents the formal task formulation of this thesis. All chosen elements based on literature's research and the justification will be introduced in chapter 3.

Bufferless optical network	**Arrivals model**	**QoS differentiation schemes**	**Algorithm**	**Analytical model**	**Simulation model**
Asynchronous OPS/ OBS with Tell-And-Go Schedule scheme	Engset traffic model The Poison arrival model	Based on access restriction	Wavelength Allocation	Paragraph 5.3.1	Paragraph 6.2.1
		Based on preemption	Preemptive drop policy	Paragraph 5.3.2	Paragraph 6.2.2
		Drop-based access restriction	Intentional Packet Dropping	Paragraph 5.3.3	Paragraph 6.2.3

Table 5.1 Task formulation of providing QoS in Optical Networks with differentiation schemes.

5.1.2 Comparison of the task of providing QoS in optical networks and analogous task in wire and wireless networks.

The idea of assuring different levels of service for different users has become a major concept in nowadays teletraffic theory. Moreover providing QoS in networks is not a trivial task due to the complicated network architecture. The main idea of providing QoS is the same for all types of networks, but the task formulation is different because of several reasons. First of all the domain in which data are transmitted and the resulting network architecture and protocols, speed and capacity have a great impact on study in this area. Some issues are dedicated only for some type of network. The main differences in formulating task of providing QoS differentiation between optical networks and traditional store-and-forward are the consequences of inability of using queue systems to model the traffic. In traditional store-and forward networks queue algorithms in buffers can be used to isolate the traffic classes. For instance study on Active Queue Management can be found in [Wyd02] or [Cri03], where all arrived packets are stored in electronic buffer and managed according to the decision made by the AQM algorithm by dropping and reordering the packets in queue. This method is not recommended in WDM layer because of two significant reasons [Yoo00]. First of all in optical network in order to process the packets electronically the O/E and E/O conversion must be used. Such translation would increase the cost of switching device and data loss ratio. Buffering could be made by using Fibre Delay Lines, but this technique cannot replace electronic processing, because the data are delayed on the fiber of fixed length. If the size of data to buffer are increasing, implementing queue management algorithms is expensive and complex.

5.2 System Model

This section will introduce a detailed description of the elements included in testing environment. The system model is provided in an informal way using draws and text explanation due to assure the good understanding of mechanisms and the way that environment behave. As mention before this thesis address only some subarea of providing QoS in All-Optical networks and some limitations have been introduced. The proposed architecture is constructed in such way to satisfy both OBS and OPS network requirements. For simplification we will use term packets in meaning both packet and bursts. The switch architecture is valid for OBS networks with Tell-And-Go scenario and asynchronous bufferless OPS network. Presented traffic model based on the Engset Lost Calls Cleared Traffic model presented in [Ive02].

5.2.1 Switch architecture.

For purpose of this work an asynchronous optical packet switch with full wavelength conversion and no internal blocking is being considered, based on research in [Øve05b]. As shown on Figure 4.1 this device consist of M input and output fibers, where each fiber provide N wavelengths using wavelength-division multiplexing technology.

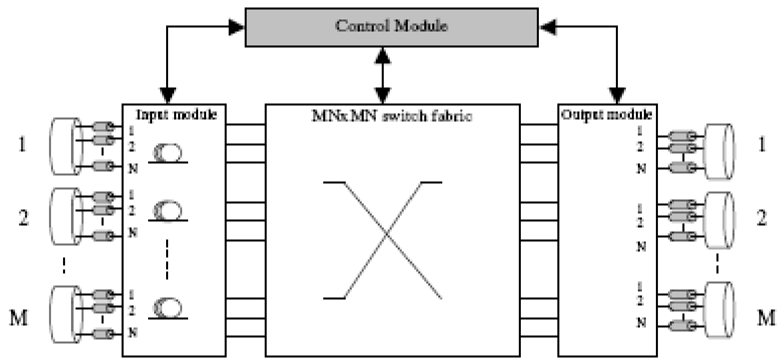


Figure 5.1 An optical packet switch with full-range output wavelength converters placed at each output wavelength (from [Øve03a]).

Due to the fact that the device work in asynchronous mode the packet can arrive to an input wavelength at any instant. In such architecture the main concern is reducing Packet Loss Ratio. The switch works as follows: when a packet arrives its header is being processed electronically while the payload is buffered using Fibre Delay Lines. Based on the information extracted from the header the control module decides which output fiber and wavelength the packet id switched to. Presented architecture assumes, that the traffic pattern is uniform, so on every output fibre the load is the same. This assumption allows limiting the research to Packet Loss Ratio on a single output fibre. Such approach has been made in most studies in this area, for instance [Øve04a]. [Mah01]. Based on these assumptions we can introduce the routing probability as shown on Figure5.2.

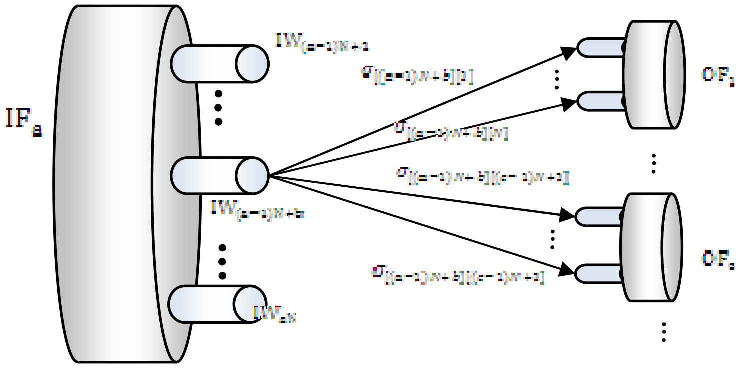


Figure 5.2 Routing probabilities in the considered optical packet switch (from [Øve05b])

According to [Øve05b] we can denote following variables:

- Input fiber a : $1 \leq a \leq N$
- Input wavelength b: $1 \leq b \leq M$ on input fiber IF_a as $IW_{(a-1+b)}$ $(1 \leq (a-1)M \leq MN$
- Output fiber c: $1 \leq c \leq N$
- Output wavelength d: $1 \leq d \leq M$ on output fiber OF_c as $IW_{(c-1+d)}$ $(1 \leq (c-1)M \leq MN$.
- Physical input wavelength θ_b, on which incoming packets are transmitted
- Physical output wavelength θ_d, on which outgoing packets are transmitted

It can be noticed, that for $b = d$, the packets are transmitted on the same physical wavelength and no convesion is need. If $b \neq d$ the input wavelength θ_b must be converted to output wavelenght θ_d.

5.2.2 General traffic model

In this section a traffic model and arrival model will be introduced. In the analyzed environment two service classes are considered: low priority class called LP and high priority class called HP correspondingly. As indicated before we focus on the load on output fibre, which provides N wavelength. This consider fibre is called the “tagged output fibre”. Each of this wavelength can be accessed by the packet from all M*N input wavelength. Presented traffic model is based on [Øve05b], where study on traffic modeling and comparison of arrivals models suitably for OPS/OBS networks have been delivered. In this thesis we adopted Engset Arrival Model. Using this pattern is recommended by authors in [Sto03][Zha03a].. However, in order to obtain analytical result of proposed differentiation schemes we will simplify this model and use Erlang Arrival Model.

Firstly we introduce traffic model without differentiation the service classes (the best-effort scenario).

- The packet service times random variables such that they are independent from each other and have the same probability distribution (independent and identically distributed i.i.d random values).
- Packets arrive on input wavelength $IW_{(a-1)N+b}$: $(1 \leq (a-1)N + b \leq MN)$ according to Pure Chance Traffic type Two (PTC-II).[Ive02]. This mean that input wavelength is modeled as an on/off source, as shown on Figure 5.3.

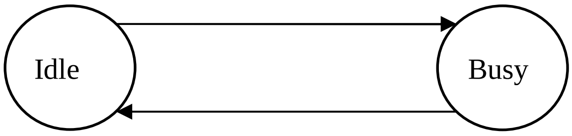


Figure 5.3 Input wavelength IW(a_1)N+b modeled as an on/off source [Øve07]

- The effect of switching time is ignored. This assumption base on the statement in [Øve04d], where authors proved that it could be disregarded if the switching time is less than 10% of the packet length.
- We denote the normalized system load in the switch as:

$$A = \frac{1}{MN} \sum_{(a-1)N+b=1}^{MN} \alpha_{(a-1)N+b} \tag{5.1}$$

- We denote $\beta_{(a-1)N+b}$ as the offered traffic for packets arriving on input wavelength $IW_{(a-1)N+b}$ in idle state and $\sigma_{(a-1)N+b}$ as the routing probability that packets are routed from $IW_{(a-1)N+b}$ to the tagged output wavelength.

- The traffic offered by input wavelength $IW_{(a-1)N+b}$ to output fiber OF_c is:

$$\vartheta = \alpha\sigma = \frac{\beta}{M(\beta+1)} \tag{5.2}$$

- The normalized system load on output fiber OF_c is:

$$A = M\vartheta = \frac{1}{\beta+1} \tag{5.3}$$

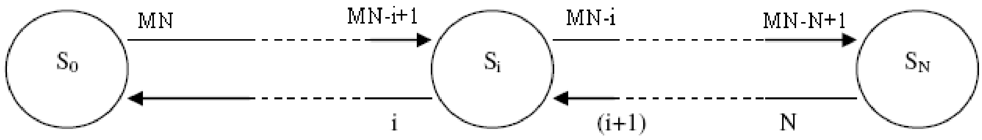
- The arrival intensity for packets routed from input wavelength $IW_{(a-1)N+b}$ to output fiber OF_c is:

$$\gamma = \frac{\vartheta}{1-\vartheta} = \frac{1}{M+\frac{M}{\beta}-1} \tag{5.4}$$

- The arrival intensity per idle input wavelength that routes packets to the tagged output fiber is:

$$\lambda = \vartheta\mu \tag{5.5}$$

- The tagged output fiber is modeled as a one-dimensional Marcovian chain shown on Figure: , where i is number of busy wavelength:



¶Figure 5.4 Markov chain of the Engset Arrival Model.

According to [IVE02] if we denote Q_i as the probability of being in state S_i, the state probabilities are given as:

$$Q_i = \frac{\binom{MN}{i}\vartheta^i}{\sum_{j=0}^{N}\binom{MN}{j}\vartheta^j} \quad \text{where } 0 \le i \le N \tag{5.6}$$

Based on this we can deliver steady state equation:

$$Q_i = \frac{\binom{MN}{i}\vartheta^i}{\sum_{j=0}^{N}\binom{MN}{j}\vartheta^j} = \frac{\frac{(MN)!}{(MN-i)!\,i!}\vartheta^i}{\sum_{j=0}^{N}\binom{MN}{j}\vartheta^j} = \frac{\frac{(MN)!}{(MN-i-1)!\,(i-1)!\,(MN-i)i}\vartheta^{i-1}\vartheta}{\sum_{j=0}^{N}\binom{MN}{j}\vartheta^j} = Q_{i-1}\frac{\vartheta}{(MN-i)i} \tag{5.7}$$

Based on Equation (5.7). we get:

$$(MN-i)i\mu Q_i = Q_{i-1}\lambda \tag{5.8}$$

This equation can be simplified, when we assume an infinite number of input wavelengths, and that packets arrive to output fibre OFc according to a pure Poisson process with intensity ω.

5.3 QoS differentiation schemes and algorithms.

5.3.1 The Wavelength Allocation algorithm

The Wavelength Allocation algorithm is based on access restriction methods and the assumption, that a subset of the available resources is exclusively reserved for higher-priority traffic.[Bjø02],[Che03] The access restriction approach to providing QoS differentiation scheme appear as an idea of differencing quality service in optical networks together with research on optical network performance. A detailed study on wavelength allocation issues and access restriction scheme can be found in [Cal02]. The Wavelength Allocation Algorithm was developed for instance in [Yan06][Øve03b], where authors introduced analytical models and in [Øve03a] where simulations have been performed.

In presented study two service classes are assumed and the possible conversion looks as follows. In each of M fibers n = N_L from N wavelength are accessible by both classes, while is N_H = (N-n) is dedicated to service the class with higher priority. According to [Øve05b] with full wavelength conversion all wavelength are treated equally, and it does not matter which wavelength is busy, but only how many is taken. When the packet arrives on the output fiber it could be processed in two ways dependently on the class service information extracted from header. If the packet belongs to class with higher priority it can access one of the N wavelength on the tagged output fiber, while the packet from lower priority class can be switched to one of n (N_L) wavelength on the output fiber. Let n_a be a number of available wavelengths on the tagged output fiber. In such case three situations can occur:

- If $n_a \geq n$, all incoming packets will be processed.
- If $n_a < n$, only packet with higher priority will be processed.
- If $n_a = 0$, all incoming packets will be discarded.

The WA algorithm is modeled using Marcovian chain as presented on Figure5.5.

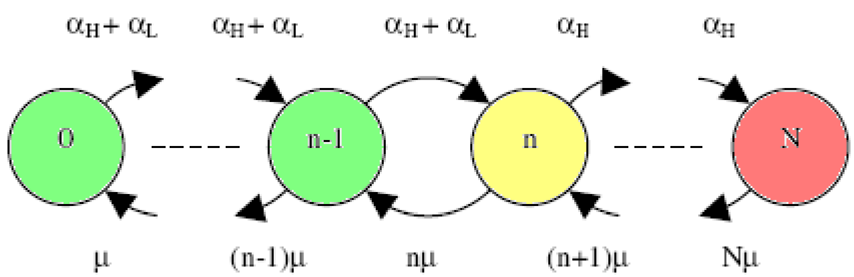


Figure 5.5 The state diagram of WA algorithm (from[Øve03a]).

Like in before considerations, being in state S_i mean that i wavelength are busy. In this case if is state probability, steady state equation are given as follows:

$$\begin{cases} i\mu \cdot Q_i = (\alpha_H + \alpha_L) \cdot Q_{i-1} & where\ 1 \leq i \leq \quad (5.9a) \\ i\mu \cdot Q_i = \alpha_H Q_{i-1} & where\ n+1 \leq i \leq \quad (5.9b) \end{cases}$$

Where

$$\sum_{i=0}^{N} Q_i = \qquad (5.10)$$

because system always is in some state.

Based on equation the state probabilities are:

$$Q_i = \begin{cases} \left(\frac{\alpha_H+\alpha_L}{\mu}\right)^i \cdot \frac{1}{i!} \cdot Q_o & where\ 1 \leq i \leq \\ \left(\frac{\alpha_H+\alpha_L}{\mu}\right)^{n} \cdot \left(\frac{\alpha_H}{\alpha_H}\right)^{i-n} \cdot \frac{1}{i!} \cdot Q_o & where\ n+1 \leq i \leq \end{cases} \tag{5.11a}$$

$$Q_o = \left[\sum_{i=0}^{n} \left(\frac{\alpha_H+\alpha_L}{\mu}\right)^i \cdot \frac{1}{i!} + \left(\frac{\alpha_H+\alpha_L}{\mu}\right)^{n} \sum_{i=n+1}^{N} \left(\frac{\alpha_H}{\alpha_H}\right)^{i-n} \cdot \frac{1}{i!}\right] \tag{5.11b}$$

According to the Equations (5.10) and (5.11) and previous discussion we can obtain PLR for both classes:

- The high priority class is lost only when the system is in state , so

$$PLR_{WA}^{H} = \tag{5.12}$$

- The low priority class is lost only when the system is in state from to , so

$$PLR_{WA}^{L} = \sum_{i=n}^{N} Q_i = Q_N + \sum_{i=n}^{N-1} Q_i = PLR_{WA}^{H} + \sum_{i=n}^{N-1} \tag{5.13}$$

From Equation (5.13)it is clear that: $PLR_{WA}^{H} \leq PLR^{L}$, what mean that traffic from higher priority class are better threated and the probability of losing packets is lower. Moreover, if n=N the PLR are equal for both classes, what refers to the best-effort scenario.

Presented schema can be expanded for more than two service classes. For instance if the network provide M service classes, for each of class we align certain number of wavelength as shown on Figure5.6

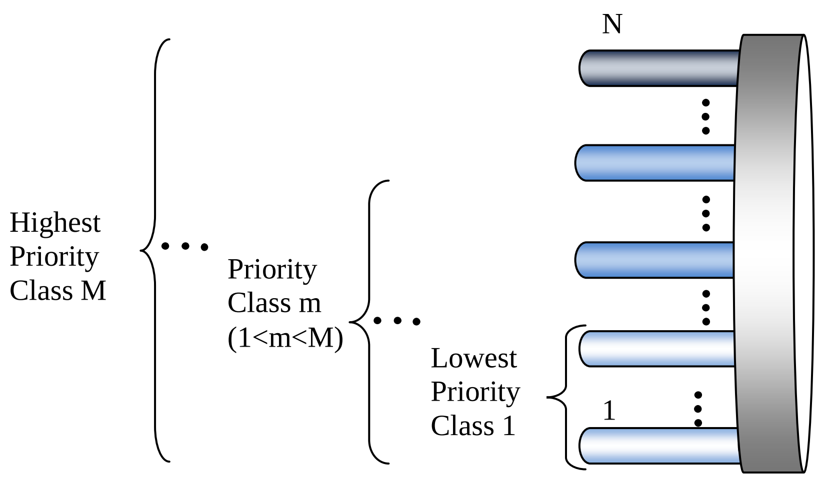


Figure 5.6 Wavelength alignments in network with multi service-classes.

5.3.2 The Preemptive Drop Policy algorithm.

The Preemptive Drop Policy based on the assumption that all free resources are available to all traffic. The preemption occurs when the high-priority packet take over the wavelength currently transmitting the low-priority packet, and no other is free. The idea of preemption shown on Figure 5.7 can lead to following possible situations, when packet are lost:

- The LP packet is being transmitted while HP packet arrive. The LP packet is drop and the HP packet take the wavelength (situation (a)).
- The HP packet is being transmitted while LP packet arrive. The LP packet is drop. (situation (b)).
- The HP packet is being transmitted while HP packet arrive. The incoming HP packet is drop. (situation (c)).

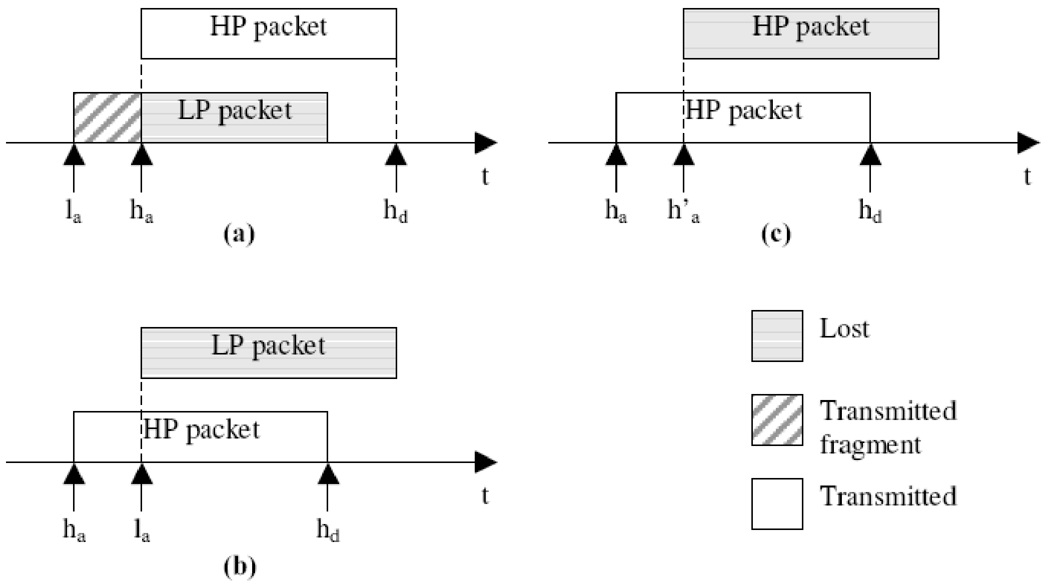


Figure 5.7 Possible preemption scenarios with PDP(from[Øve03a])

The idea of this approach is to introduce a parameter, which describes the probability of success preemption. Let $p : 0 \le p \le 1$ be the probability of success preemption, we can now observe following situation:

- For p the packets form higher priority class will not be able to preempt wavelength serving lower priority traffic. It is the situation in best-effort scenario.
- For p the packets form higher priority class will always preempt wavelength if only it is serving lower priority traffic.
- For $0 < p$ we can control the level of PLR for higher priority traffic. However, with probability 1 the preemption fails.

The Preemptive Drop Policy algorithm is modeled using two-dimensional Marcovian chain as presented on Figure 5.8. The general system state in one time instance is a pair of states $(S_i^H, S_j^L) : i + j = I$ where S mean that i wavelength are currently occupied by high priority packets, and mean that low priority packets are being transmitted on j wavelengths. According to the state diagram at any time instance if all wavelength are occupied and at least one is transmitting low priority packet the high priority packet can preempt with probability p.

The lost state occurs when $i + j =$, so at the begin we introduce unit step function:

$$y_x = \begin{cases} 1 & if \quad x < l \\ 0 & if \quad x = l \end{cases} \tag{5.14}$$

The steady state equation for each node in the diagram is given as follows:

$$Q_{i,j} \cdot \left((i+j)\mu + \alpha_H + \alpha_L\right) = Q_{i-1,j} \cdot \alpha_H \cdot y_{N-i} + Q_{i-1,j} \cdot \left((i+1)\mu\right) for \ 0 \leq i +$$

(5.15a)

$$Q_{i,j} \cdot (p \cdot \alpha_H \cdot y_i + N\mu) = Q_{i-1,j} \cdot \alpha_H \cdot y_j + Q_{i,j-1} \cdot \alpha_L \cdot y_i \qquad for \quad i + j = \tag{5.15b}$$

Where

$$\sum_{i=0}^{N} \sum_{j=0}^{N-i} Q_{i,j} = \tag{5.16}$$

According to the Equations (5.15) – (5.16) and previous discussion about the preemption probability we can obtain PLR for both classes:

- The high priority class is lost only when all wavelength are occupied by the high priority traffic or when the preemption fails, so

$$PLR_{PDP}^{H} = \frac{\alpha_H \cdot Q_{N,0} + \sum_{i=0}^{N-1}(1-p) \cdot \alpha_H \cdot Q_{i,N-i}}{\alpha_H \cdot \sum_{i=0}^{N} \sum_{j=0}^{N-i} Q_{i,j}} = Q_{N,0} + \sum_{i=0}^{N-1}(1-p) \cdot Q_{i,N} \tag{5.17}$$

- The low priority class is lost only when the system is in state from to , so

$$PLR_{PDP}^{L} = \frac{\alpha_L \cdot Q_{N,0} + \sum_{i=0}^{N-1}(\alpha_L + p \cdot \alpha_H) \cdot Q_{i,N-i}}{\alpha_L \cdot \sum_{i=0}^{N} \sum_{j=0}^{N-i} Q_{i,j}} = Q_{N,0} + \sum_{i=0}^{N-1}\left(1 + p \cdot \frac{\alpha_H}{\alpha_L}\right) \cdot Q_{i,N-i} \tag{5.18}$$

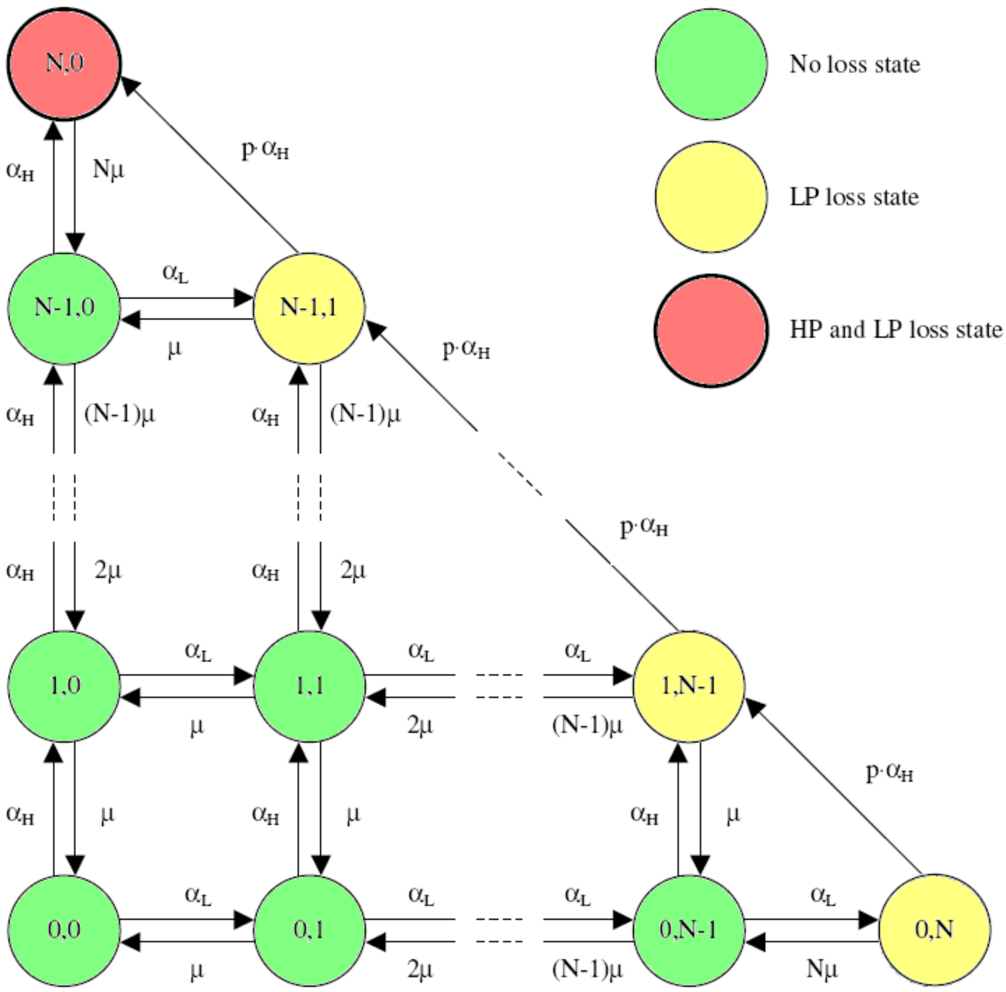


Figure 5.8 State diagram of the PDP (from[Øve03a])

From Equations (5.18) and (5.19) it is clear that: $PLR^H_{PDP} \leq PLR^L_{P_i}$,for $0 < p \leq$ what mean that traffic from higher priority class are better treated and the probability of losing packets is lower. Moreover, if $p =$the PLR are equal for both classes, what refers to the best-effort scenario.

Presented schema can be expanded for more than two service classes. However, the dimension of Marcovian chain is strictly connected with the number of class service. For instance if M service classes would be provided, the state diagram is represented by M-dimensional Marcovian chain, what make it very hard to obtain analytical results.

5.3.3 Dropping based QoS differentiation scheme

Dropping based QoS differentiation scheme based on the assumption that low-priority traffic could be dropped before reaching the output fiber with a certain probability. At the output fiber packets are treated equally and only loss can be caused by contention. The algorithms of differentiation scheme based on dropping were introduced in [Zha03b] [Che01]. In this thesis we will consider the Intentional

Packet Dropping algorithm, which basis on the general assumption of this scheme.

The main idea of this scheme is shown on Figure 5.9.

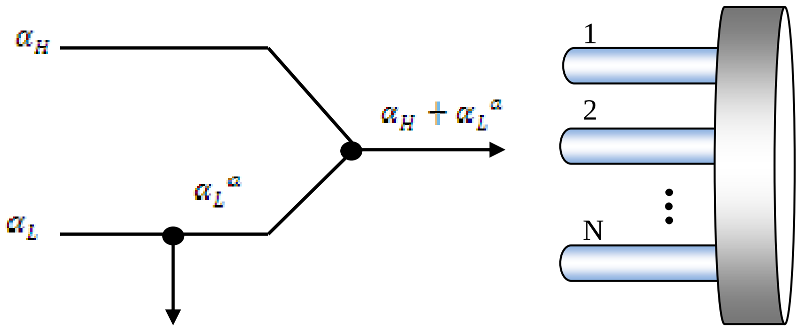


Figure 5.9 Traffic model for Intentional Packet Dropping (from [Øve06a])

The packets from lower priority class are intentionally dropped with some probability denoted as $d: 0 < d < 1$, which mean $\alpha_L^d = d \cdot \alpha_L$ is lost and to the output fiber arrives $\alpha_L^a = (1-d) \cdot \alpha_L$. It is very important to underline, that if $d = 1$ all lower priority packet are dropped and for $d = 0$ all packets are threated equally. This algorithm is probably the simplest QoS differentiation method [Nor03] due to two reasons. Firstly there is no reason for obtaining system state information for the switch. Secondly it requires only implementing dropping module in the switch.

Following the [Øve06a] we get the statement "Since the arrival processes for class 0 and class 1 traffic follow a Poisson process, according to the splitting property, the resulting process after the drop mechanism is also a Poisson process". Moreover following the statements in [IVE02] according to merging property we can denote that final arrival process to the output fibre is a Poison process with total intensity $\alpha_H + \alpha_L^a$. Both properties with explanation can be found in [IVE02]. In order to evaluate the Packet Loss Ratio we introduce the Erlang Loss Formula (named also Erlang B Formula). The Erlang B Formula assumes an infinite number of sources (in our case sources are the input wavelength), which offer traffic to N resources (this refers to the N output wavelength in consider model). Furthermore, because of this assumption the rate of arrivals of new incoming request is constant and equal to λ. The rate of outgoing serviced request is equal to the number of currently processed times by packet service time denoted as μ^{-1}. The Erlang Loss Formula is used in loss system to calculate the blocking probability. In loss system we assume that, if a request cannot be served at once due to the lack of available resources, it is lost.

The Erlang Loss Formula is given as:

$$E(A, N) = \frac{\frac{A^N}{N!}}{\sum_{i=0}^{N} \frac{A^i}{i!}} \tag{5.19}$$

Where:

- E is the blocking probability
- A is the normalized system load
- N is the number of resources (output wavelength)

As mentioned before the loss probability is dependent on the contention, which can be evaluated using Erlang Loss Formula in following way:

- The PLR for packet from higher priority class is evaluated as follows:

$$PLR^{H}_{IPD} = E\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}, N\right) = \frac{\frac{\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}\right)^{N}}{N!}}{\sum_{i=0}^{N}\frac{\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}\right)^{i}}{i!}} \tag{5.20}$$

- The PLR equation for packet from lower priority class is:

$$PLR^{H}_{IPD} = d + (1-d)\cdot E\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}, N\right) = d + (1-d)\cdot \frac{\frac{\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}\right)^{N}}{N!}}{\sum_{i=0}^{N}\frac{\left(\frac{\alpha_H+\alpha_L{}^{a}}{\mu}\right)^{i}}{i!}} \tag{5.21}$$

From the equations (5.20) and (5.21) following statements are concluded:

- If d=0 $\mathrm{PLR}^{\mathrm{H}}_{\mathrm{IPD}} = \mathrm{PLR}^{\mathrm{L}}_{\mathrm{IPD}}$, what refers to the best-effort scenario.
- If d increases $\mathrm{PLR}^{\mathrm{H}}_{\mathrm{IPD}} < \mathrm{PLR}^{\mathrm{L}}_{\mathrm{IPD}}$, so the packet from higher priority class experience the lower Packet Loss Ratio.
- For d=1 all low priority packet are discarded before reaching the output fibre.

Presented schema can be expanded for more than two service classes by adding loss probability for each traffic class. However, the study in this subject require precise research and tests in order to choose appropriate probabilities for each class. This schema can be also used in providing absolute end-to-end QoS, which was studied in [Zha03b][Und04].

CHAPTER 6

SIMULATIONS OF ALGORITHM PROVIDING QOS DIFFERENTIATION IN OBS/OPS NETWORKS

In this chapter simulations will be performed in order to present the qualitative and quantitative comparison of algorithms introduced previous according to the Packet Loss Ratio. Performed simulations includes two steps:

- As each of the presented schemes has the steering parameter, we will firstly simulate each algorithm separately in order to choose the best value for the attribute.
- In second step we will compare all three algorithms with each other based on the chosen crucial quality parameter – PLR.

6.1 Simulator

The engineering of networking is one of the main focus domains in nowadays computer science. The need for testing and developing different tools, mechanisms and ideas, that could improve delivering services caused that nowadays we have a lot of available simulators and applications. The most popular network simulators are ns-2 [Isi08], OMNet++[Omn08], etc.. However, as mention before the limitation of this thesis as well as the assumptions allow us to use protocol independent discrete event simulator. Nowadays there are a lot of such tools, for example Matlab [Mat08] or DEMOS[Dem08] (Discrete Event Modeling on Simula). However for purpose of this thesis we decided to implement own application. The detail description can be found in Appendix A. All simulation described in this chapter are performed with OpticalSwitchSimulation tool.

6.2 Algorithm's analysis

The first step in simulation process is to perform the analysis of the impact of steering parameter in each algorithm on the Packet Loss Ratio. Several simulations have been run until we obtain desired level of convenience and the representative results.

6.2.1 System model

In order to perform convenient and representing results of the simulation for each algorithm we assume the following:

- Number of input fiber 10.
- Number of wavelength per fiber 20.
- Number of simulation step 15000.
- The number of simulations for each parameter 15.
- The traffic model is based on the Engset Arrival Model introduced in chapter 5.

6.2.2 The Wavelength Allocation algorithm

For simulating the WA algorithm we assumed that n wavelengths can be access by both priority packets. This mean that n<N is the share of both classes. Figure 6.1 the dependency of PLR for each class on variable n.

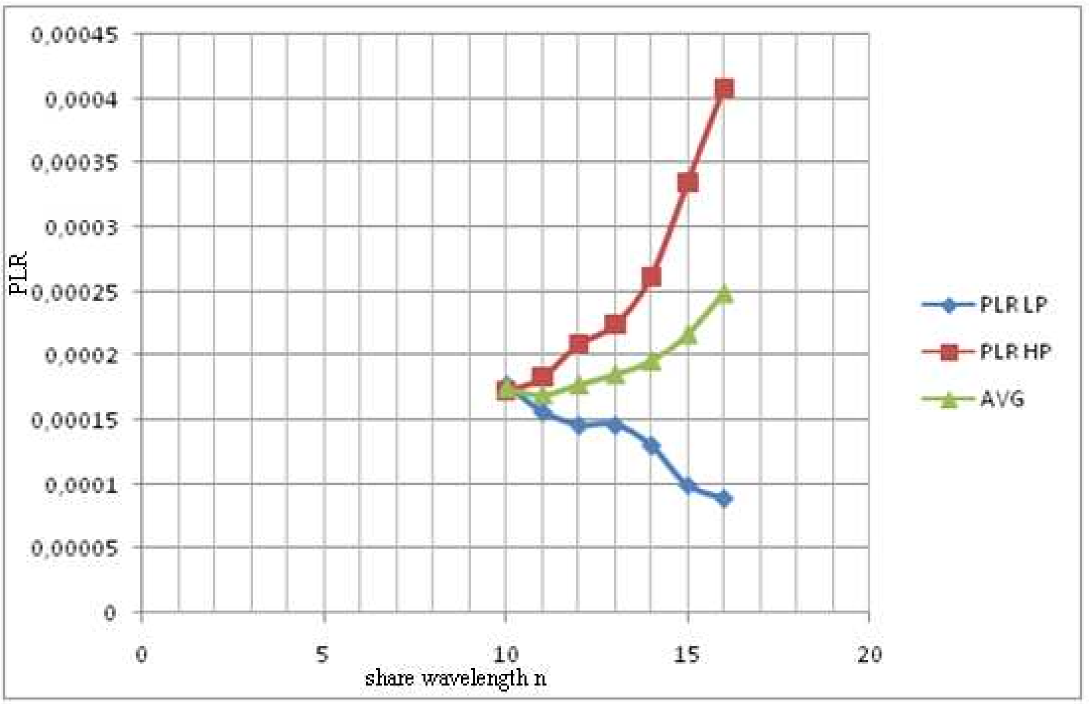


Figure 6.1 Function PRL of variable n for the WA algorithm

As can be seen on Figure above PLR for high priority class traffic decreases as the n decreases, which is because more resources are reserved exclusively to higher class traffic. Moreover, the average Packet Loss Ratio increases with growing n. If we compare this situation to the best-effort scenario it is easy to notice the statement that implementing this schema to optical networks gives worse overall results according to the PLR. However for the further analysis and comparison of differentiation schemes algorithms the n parameter was set on the number of 14. The average results after performing certain number of simulations can be found in table 6.1

Number of shared wavelenght	10	11	12	13	14	15	16
HP arrivals	191018	191018	191018	191018	191018	191018	191018
LP arrivals	191324	191324	191324	191324	191324	191324	191324
Total arrivals	382342	382342	382342	382342	382342	382342	382342
Total lost HP packet	34	30	28	28	25	19	17
Total lost LP packet	33	35	40	43	50	64	78
PLR^{H}	0,000173	0,000183	0,000209	0,000225	0,000262	0,000335	0,000408
PLR^{L}	0,000178	0,000157	0,000146	0,000146	0,000131	9,93E-05	8,89E-05
PLR^{avg}	0,000175	0,00017	0,000178	0,000186	0,000196	0,000217	0,000248

Table 6.1 The average results after perform 15 simulation

6.2.3 The Preemptive Drop Policy algorithm

For simulating the PDP algorithm we tested the Packet Loss Ratio by manipulating the preemption probability parameter. The higher the probability was the often the preemption occur. However, as the preemption take place only when contention on the output wavelength occur the average PLR is on almost the same level. Figure 6.2 presents the dependency of PLR for each class on preemption probability.

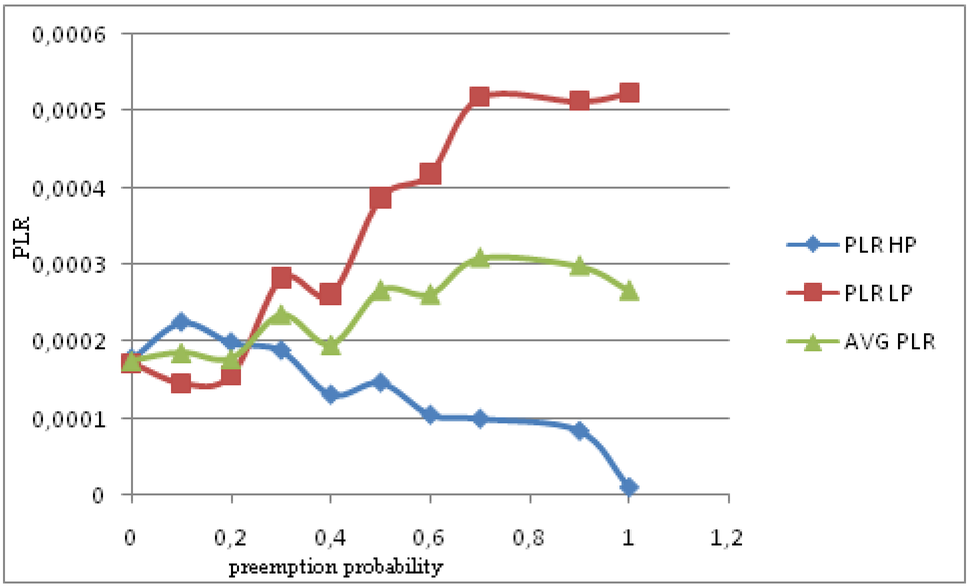


Figure 6.2 The PDP as the function if preemption probability.

As can be seen on The Figure 6.2 the preemptive Drop Policy algorithm fulfill the expectation of quality differentiation. The lower traffic decrease with increasing the probability of preemption. However, as the preemption take place only when contention on the output wavelength occur the average PLR is on almost the same level. The average numerical results can be seen in Table 6.2.

Preemption probability	0	0,2	0,3	0,5	0,7	0,9	1
HP arrivals	191018	191018	191018	191018	191018	191018	191018
LP arrivals	191324	191324	191324	191324	191324	191324	191324
Total arrivals	382342	382342	382342	382342	382342	382342	382342
Total lost HP traffic	34	38	36	28	19	16	2
Total lost LP traffic	33	30	54	74	99	98	100
PLR^H	0,000178	0,000199	0,000188	0,000147	9,95E-05	8,38E-05	1,05E-05
PLR^L	0,000172	0,000157	0,000282	0,000387	0,000517	0,000512	0,000523
PLR^{avg}	0,000175	0,000178	0,000235	0,000267	0,000308	0,000298	0,000267

Table 6.2 The statistics of PLR with PDP algorithm

6.2.4 The Intentional packet dropping algorithm

The third approach to service differentiation is based on dropping scheme. The Intentionally Packet Dropping scheme also address the requirements of QoS. However, the main disadvantage of this method is possible underutilization of resources. As the lower priority packet can be dropped although there exists a free wavelength on the output fiber.

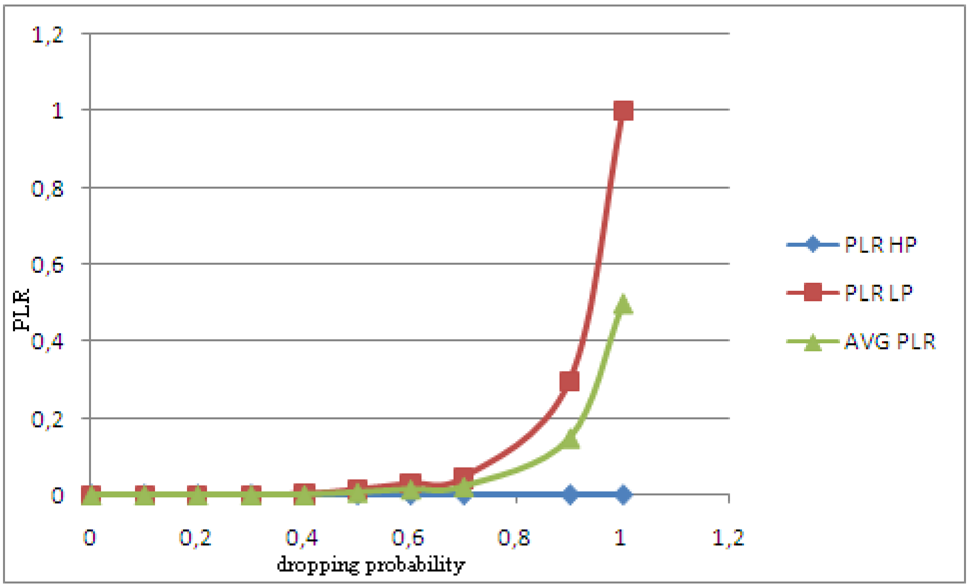


Figure 6.3 PLR function of the dropping probability

On Figure 6.3 the dependence between PLR and growing dropping probability. We can easily notice that witch increasing value of this parameter we decrease the lower priority traffic. Moreover, the PLR for high priority packets is stable on the same level. The average numerical results can be seen in Table 6.2.

D	0,1	0,3	0,5	0,7	0,9	1
Hp	191018	191018	191018	191018	191018	191018
Lp	191324	191324	191324	191324	191324	191324
Total	382342	382342	382342	382342	382342	382342
Lost h	54	90	17	30	30	43
Lost l	102	443	823	7888	95976	191018
PLR H	0,000534	0,002319	0,004308	0,000157053	0,000157	0,000225
PLR L	0,000533	0,002315	0,004302	0,041228492	0,501641	0,940812
PLR	0,000408	0,001394	0,002197	0,020709208	0,2511	0,470895

Table 6.3 The statistics of PLR with IDP algorithm

6.3 Comparison of the presented schema

Previous section presented the numerical evaluation of presented algorithms that support providing Quality of Service based on differentiation schemes. Received results allow to compare those three approaches to QoS. Table 6.4 presents the numerical values of Packet Loss Ratio for each of mechanisms.

	IPD	PDP	WA
PLR^{H}	2,47E-04	0,000196	0,124878
PLR^{L}	0,000306	0,000165	0,186461
PLR^{avg}	0,000247	0,000248	0,001212

Table 6.4 The comparison of the WA, PDP and OPD algorithm according to PLR.

Comparison of presented schemas is not a trivial task. On one hand we have Packet Loss Ratio as a number, so theoretically it would be a simple decision, what differentiation schema is better to use. On the other hand, presented approaches do not address all issues existing in Optical Networks. Nevertheless, based on results obtained in this chapter, we may say the following statements.

- According to Table 6.4 the Preemption Drop Policy hw algorithm gain the best results with the lowest Packet Loss Ratio.
- The Wavelength Allocation and Intentional Packet Dropping algorithms may cause underutilization of available resource, because of keeping stand-by wavelength in WA or due to the lack of awareness about the state on output fiber in case of IPD method.
- Regarding the service provided to traffic class from table 6.4 we can see that $PLR_{PDP}^{H} < PLR_{WA}^{H}$ and $PLR_{PDP}^{L} < PLR_{WA}^{L}$, so implementing PDP results in lower Packet Loss Ratio for both classes of service when comparing WA and PDP algorithms
- Comparing PDP and IPD we can see, that $PLR_{IPD}^{H} < PLR_{PDP}^{H}$, but $PLR_{PDP}^{L} < PLR_{IPD}^{L}$, so it could be say that implementing Intentional Packet Dropping rather improve the service provided to the higher priority traffic, than differ traffic into classes.

CHAPTER 7

SUMMARY

The purpose of presented study was to investigate the given opportunities with optical networking with an object of providing Quality of Service. The main hypothesis of this work will be now evaluated, as well as we give the answers to research questions presented at the beginning of this thesis.

7.1 Hypothesis evaluation

The main hypothesis of this thesis was "What is the most suitable QoS differentiation scheme according to the PLR?" Presented work includes both analytical and empirical consideration in this. According to performed research in chapter 5 and 6 the answer is not simple. As mention before Optical Networks are large area of research, especially that the nowadays technology cannot address most of the presented concepts. Moreover each differentiation scheme provides only the general overview of the differentiation mechanisms, and many implemented algorithms are being tested in not identical environment. However, based on this study when we limited to presented system model, we can claim that differentiation scheme based on preemption is most accurate for providing QoS in Optical Packet/Burst Network, due to several reason:

- Comparing to others scheme based on preemption does not cause the resource underutilization, which is great advantage while concerning the growing demands on internet services.

- This scheme based on the idea of sharing all resources between different service classes, so does not need complicated mechanisms of access restriction or resource allocation. However, the mechanisms that service preemption require more processing in comparison to others presented in the work.

- Performed analyses shown, that algorithm based on preemption decreases the crucial Packet Loss Ratio parameter both for low and high priority class.

7.2 Conclusions

Research Question 1: What are the main differences while implementing QoS in optical networks compared to the wire and wireless networks?

Providing Quality of Service in networks is not a trivial task due to the complicated network architecture. The main idea of providing QoS is the same for all kinds of telecomunication networks, but the differences starts when the network type is chosen. First of all, the domain in which data are transmitted and the resulting network architecture including protocols, speed and capacity have a great impact on study in this area. Some issues are dedicated only for some type of network. The main differences in implementing Quality of Service between optical networks and traditional store-and-forward based on the consequences of inability of using queue systems to model the traffic. Transferring data in optical domain causes the problems with processing them in switching devices, due to the lack of optical RAM. As the nowadays technology has no answer for this issue the packets/bursts are processed electronically with the O/E and E/O conversion. Such translation increases the cost of switching device and data loss ratio, as well as the complexity of used tools. Moreover, the next generation optical networks would work only in optical domain, but this introduces new protocols, routing mechanisms, etc, what make the differences even stronger. The other important difference is fact that most of the research in optical networks are only theoretical and have not been tested in the reality. However, the quickly developing technology may give the tool soon.

Research Question 2: Which algorithm based on differentiation scheme gives the best results according to the packet loss ratio?

Performed analyses and simulation, as well as the literature survey indicated that choosing the differentiation scheme has great impact on ensure QoS in Optical Networks. On the other hand choice of type of service, what quality parameter are being under consideration and the network architecture impacts on the model of the differentiation scheme as well. Moreover, it should be underlined that the differentiation schemes present only the idea of mechanisms of providing QoS.

This thesis focuses on three differentiation schemes and for each we have chosen an algorithm that realizes the mechanisms:

- Based on access restriction with Wavelength Allocation algorithm,
- Based on preemption with Preemptive Drop Policy algorithm,
- Based on dropping wit Intentionally Packet Dropping algorithm.

All three algorithms were investigated in order to obtain analytical and numerical results according to mineralize Packet Loss Ratio.

Implemented Intentionally Packet Dropping algorithm is one of the simplest, due to the fact, that it only adds decision module, which will drop low priority packet with some predefined probability. This has both advantage and disadvantage. This algorithm gives the simply tool to introduce the QoS differentiation into Optical Networks, but on the other hand may cause the resource underutilization, due to the lack of awareness of the state of the system, when packets/bursts are dropped although wavelength on the output fiber is available.

The Wavelength Allocation algorithm is also simply to implement, as the switch only need to count currently busy wavelength and the packet/burst priority that is being transmitted. This requires less processing in the device, but caused the situation where low priority packet id being discarded, because no wavelength from shared resources are available, although there are free resources align to the higher priority traffic.

The Preemptive Drop Policy threats all resources equally and if possible give the available wavelength to the arriving packets/bursts. The higher priority traffic has, however, the power to take over the resources from lower priority traffic. This algorithm has several significant advantages. Firstly all wavelengths are available to all traffic classes, what gives better resource utilization. According to performed analyses it gives the best PLR for both classes. However, evaluating this algorithm for more than two classes is a complex task.

Nevertheless, it can be implemented to serve any desired number of service classes.

All presented algorithm have both advantages and disadvantages, but if we focus on the minimizing PLR the best results were achieved for Preemptive Drop Policy.

7.3 Further work

The All-Optical Networks are now in very early stage of developing, due to the limits of nowadays technology, such as lack of switching devices that work in optical layer. The idea of performing research in this domain is to start the study with basics concepts and successively addressing new issues or features of Optical Network. As the good start for investigating this area of interest we begin with providing QoS, which seems to be to be a crucial issue in next generation of Optical Networks. Due to the fact that there are many issues related to the optical networking, the further work in this area could consider different directions. A good idea could be considering the contention resolution problems and their impact on already presented state-of-art.

The purpose of presented study was to investigate the given opportunities with optical networking with an object of providing Quality of Service. The main hypothesis of this work has been evaluated, as well as we have given the answers to research questions presented at the beginning of this thesis.

REFERENCES

[Bjø02a] S. Bjørnstad, N. Stol, D. R. Hjelme, *An Optical Packet Switch Design with Shared Electronic Buffering and Low Bit Rate Add/Drop Inputs*, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 69-72, 2002.

[Bjø02b] S. Bjørnstad, N. Stol and D.R. Hjelme, *Quality of service in optical packet switched DWDM transport networks*, in: Proceedings of SPIE Asian-Pacific Optical and Wireless Communications Conference and Exhibition (APOC), Proceedings of SPIE, Vol. 4910, (2002) pp. 63–74.

[Bla98] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss. *An architecture for differentiated service.* Request for Comments (Informational) 2475, Internet Engineering Task Force, December 1998.

[Bra94] R. Braden, D. Clark, and S. Shenker. *Integrated services in the internet architecture: an overview.* Request for Comments (Informational) 1633, Internet Engineering Task Force, June 1994

[Cal02] F. Callegati, G. Corazza, C. Raffaelli, *Exploitation of DWDM for Optical Packet Switching With Quality of Service Guarantees*, IEEE Journal on Selected Areas in Communications 20(1) (2002) 190-201.

[Che01] Y. Chen, M. Hamdi, D.H. K. Tsang, C. Qiao, *Providing proportionally differentiated services over optical burst switching networks*, Proc. IEEE Globecom'01, pp.1510–1514, Nov. 2001.

[Che03] Y. Chen, H. Wu, D. Xu and C. Qiao, *Performance analysis of optical burst switched node with deflection routing*, in: Proceedings of IEEE International Conference on Communication (ICC), Vol. 2, (2003) pp. 1355–1359.

[Dem08] Discrete Event Modeling On Simula (DEMOS), official Web site *www.demos2k.org/*, (access Jan 2008)

[Dur96] T. Durhuus, B. Mikkelsen, C. Jorgensen, S.L. Danielsen, K.E. Stubkjaer, *All-optical wavelength conversion by semiconductor optical amplifiers*," J. Lightwave Technol., vol. 14, pp. 942–945, 1996.

[Gau04] C. M. Gauger, M. Köhn, J. Scharf. *Comparison of contention resolution strategies in OBS network scenarios*, Proceedings of the 6th Int'l Conference on Transparent Optical Networks (ICTON) 2004, Wroclaw/PL, 2004.

[Grz02] A. Grzech *„Sterowanie ruchem w sieciach teleinformatycznych (In polish)"*, 2002.

[Ive02] V.B. Iversen, *Teletraffic engineering*, ITU-D, 2002.

[Isi08] The Network Simulator ns-2*: http://www.isi.edu/nsnam/ns/* (access August 2008)

[Jaj01] Jajszczyk A.: *Ewolucja sieci stacjonarnych (In polish)* Przegląd Telekomunikacyjny i Wiadomości Telekomunikacyjne, nr 1, 2001.

[Laz07] A. Lazzez, Y. Khlifi, S. Guemara El Fatmi, N. Boudriga , M.S. Obaidat, *A novel node architecture for optical networks: Modeling, analysis and performance evaluation,* Elsevier, Computer Communications 30 (2007) 999–1014

[Lin08] Linktionary.com, Tom Sheldon's Encyclopedia of Networking and Telecommunications: *http://www.linktionary.com/c/core.html* (access Apr 2008)

[LN 01] Lecture Notes in Computer Science, *An All-Optical Packet-Switched Network Architecture with Support for Group Communication,* Springer Berlin/Heidelberg, January 2001, Page(s): 326-335

[Lu 04] Bin Lu; Xiaolong Yang; Min Zhang; Hong Jiang; Lemin Li, *An efficient contention resolution based on FDL and TWC for OPS networks*, the 2004 Joint Conference of the 10th Asia-Pacific Conference on Volume 1, Issue , 29 Aug.-1 Sept. 2004 Page(s): 391 - 395 vol.1.

[Maa02] A. Maach, G. V. Bochman, H. Mouftah, *Congestion Control and Contention Elimination in Optical Burst Switching,* Kluwer Telecommunication Systems 27(2-4) (2004) 115-131.

[Mah01] M.J. O'Mahony, D. Simeonidou, D.K. Hunter and A. Tzanakaki, *The application of optical packet switching in future communication networks,* IEEE Communications Magazine 39(3) (2001) 128-135

[Mat08] Matlab, official Web site, *www.mathworks.com/* (access May 2008)

[Nor03] M. Nord, S. Bjørnstad, C. M. Gauger, *OPS or OBS in the Core Network? – A Comparison of Optical Packet- and Optical Burst Switching*, in Proceedings of the 7th IFIP working conference on optical network design & modeling (ONDM), 2003.

[Omn08] OMNet++ simulator, official *website: http://www.omnetpp.org/,* (acces Aug08)

[Opt07] Optical Network Tutorial: *http://www.iec.org/online/tutorials/opt_net/* (access Dec 2007).

[Øve03a] H. Øverby, *A study on service differentiation in bufferless optical packet/burst switched networks*, in: Proceedings of Norwegian Informatics Conference (NIK), (2003) pp. 105-116.

[Øve03b] H. Øverby, *An adaptive service differentiation algorithm for optical packet switched networks*, in: Proceedings of International Conference on TransparentOpticalNetworks (ICTON),Vol. 1 (2003) pp. 158–161.

[Øve04a] H. Øverby, N. Stol, *Quality of Service in asynchronous bufferless optical packet switched networks*, Kluwer Telecommunication Systems, 27(2-4) (2004) 151-179.

[Øve04b] H. Øverby, N. Stol, *Performance modeling of asynchronous bufferless optical packet switched networks*, submitted to Elsevier Optical Switching and Networking, December 2004.

[Øve04c] H. Øverby, *Performance modeling of synchronous bufferless OPS networks*, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 22-28, 2004.

[Øve04d] H. Øverby, N. Stol, *Effects of the switching time in OPS/OBS networks*, Chinese Optics Letters 2 (3) (2004) 131–134.

[Øve05a] H. Øverby, *Quality of service differentiation, Teletraffic analysis and Network layer packet redundancy in Optical packet switched networks*, PhD thesis at the Norwegian University of Science and Technology, Department of Telematics, 2005

[Øve05b] H. Øverby, *Performance modeling of optical packet switched networks with the Engset traffic model*, accepted in OSA Optics Express, February 2005.

[Øve06a] H. Øverby, N. Stol, *QoS Differentiation in Asynchronous Bufferless Optical Packet Switched Networks*, Springer Science, Wireless Networks 12, 383–394, 2006

[Øve06b] H. Øverby, N. Stol, M. Nord, *Evaluation of QoS differentiation mechanisms in asynchronous bufferless optical packet-switched networks,* Norwegian Univ. of Science and Technology, Norway; IEEE Communications Magazine 44(8) (2006) 52-57

[Øve07] H. Øverby, *Traffic Modelling of Asynchronous Bufferless Optical Packet Switched Networks*, Computer Communications 2007;30(6):1229-1243

[Per02] S. D. Personick, *Evolving toward the Next-Generation Internet: Challenges in the Path Forward*, IEEE Communications Magazine 40(7) (2002) 72-76.

[Ram02] R. Ramaswami, K. N. Sivarajan, *Optical Networks: A Practical Perspective,* San Francisco, CA, USA: Morgan Kaufmann Publishers, Inc, 1998.

[Ram06] R. Ramaswami, *Optical Networking Technologies: What Worked and What Didn't* IEEE Communications Magazine, 44(9) September 2006, 132-139

[Son08] Synchronaus Optical Network (SONET) Transmission http://www.iec.org/online/tutorials/sonet/,(access May 2008)

[Sto03] N. Stol, H. Øverby, *A teletraffic model for service differentiation in OPS networks*, in: Proceedings of Optoelectronic and Communications Conference (OECC), Vol. 2 (2003) pp. 677–678.

[Und04] A. Undheim, H. Øverby, N. Stol, *Absolute QoS in Synchronous Optical Packet Switched Networks*, in Proceedings of the Norwegian Informatics Conference (NIK), pp. 137-148, 2004.

[Tan04] A. S. Tanenbaum: *Sieci komputerowe. Kompendium wiedzy na temat współczesnych sieci komputerowych*, (in polish) ,Helion, 2004.

[Tur99] J. S. Turner, *Terabit burst switching*, Journal of High Speed Networks 8(1) (1999) 3-16.

[Wan 01] Jian Wang, Wonhong Cho, V. Rao Vernuri, B. Mukherjee, *Improved approaches for cost-effective traffic grooming in WDM ring networks: ILP formulations and single-hop and multi-hop connections,* IEEE Journal of Lightwave Technology 19(11) (2001) 1645-1653

[Wyd02] B. Wydrowski, M. Zukerman, *QoS in Best-Effort Networks,* IEEE Communications Magazine 40(12) (2002) 44-49

[Xu 01] L. Xu, H. G. Perros, G. Rouskas, *Techniques for Optical Packet Switching and Optical Burst Switching*, IEEE Communications Magazine 39(1) (2001) 136-142.

[Yao00] S. Yao, *Advances in Photonic Packet Switching: An Overview*, IEEE Communications Magazine, 38(2), February 2000, 84-94

[Yao03] S. Yao, B. Mukherjee, S.J. Ben Yoo, S. Dixit, *A unified study of contention-resolution schemes in optical packet-switched networks*, IEEE Journal of Lightwave Technology (2003).

[Yan06] U. Yang, H. Zhang, T. Ye, Z. Shi, *Wavelength allocation algorithms for optical packet switch under limited wavelength conversion*, Optical transmission, switching, and subsystems. Conference N 4, 2006, vol. 6353 (2)

[Yoo00] M. Yoo, C. Qiao, S. Dixit, *QoS Performance of Optical Burst Switching in IP-Over-WDM Networks*, IEEE Journal on Selected Areas in Communications 18(10) (2000) 2062-2071.

[Zan00] H Zang, JP Jue, B Mukherjee, *A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks*, Optical Network Magazine, January 2000 pp 47-60

[Zha01] W. Zhao, D. Olshefski, H. Schulzrinne, *Internet Quality of Service: An Overview*. Columbia University, Technical Paper.,2001

[Zha03a] Z. Zhang, Y. Yang, *Performance Modeling of Bufferless WDM Packet Switching Networks with Wavelength Conversion*, in Proceedings of IEEE Global Telecommunication Conference (GLOBECOM), 2003

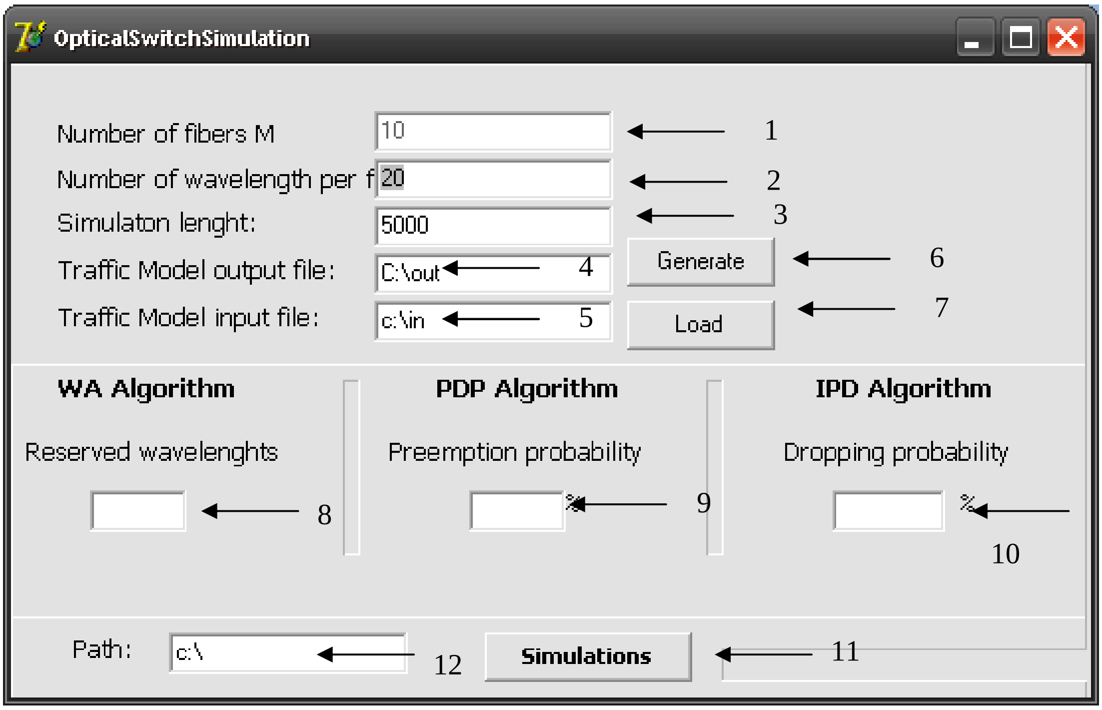
[Zha03b] Q. Zhang, V.M. Vokkarane, Biao Chen, J.P. Jue, *Early drop scheme for providing absolute QoS differentiation in optical burst-switched networks*, High Performance Switching and Routing, 2003, HPSR. Workshop on Page(s): 153- 157

APPENDIX A

THE OPTICALSWITCHSIMULATION

The OpticalSwitchSimulation is an application implemented in Delphi. In the application we can set parameters on the switch, the simulation length (steps) and the parameters of each algorithm. Meanings of the parameters were described in chapter 5.

After launch the executable file the main window appears, as shown on Figure 2. Figure 2. The main window of application OpticalSwitchsimulations



The components description and limits:

1. Number of input fiber (refers to M in chapter 5). Performed simulation shown that the best value according to the time of simulation is 10.
2. Number of wavelength per fiber should be less than 100
3. Simulation length is number of step in simulation. The step is an instance of time, where the system can change its state. Limit to 15000
4. Traffic Model output file is the path to the file in which the traffic model are saved.
5. Traffic Model input file is the path to the file from which the traffic model can be loaded.

6. Load button runs the procedure of reading the traffic model from file.
7. Generate button runs the procedure of creating traffic model. The procedure basis on the model introduced in chapter 5.
8. The WA parameter – the number of wavelength available for lower priority packets. This number cannot be greater than total number of output wavelength and if it is equal the application runs the best effort scenario.
9. The PDP parameter – the probability of success preemption in % (value from 0 to 100). If it is equal to 0 application runs the best effort scenario
10. The IDP parameter – the probability of dropping the lower priority packet. in % (value from 0 to 100). If it is equal to 0 application runs the best effort scenario
11. The Simulation button runs the simulations with previously set parameters.
12. The path to simulation destination folder.

The output file for each simulation is in cvs format and contains following result:

- Number if arrived packets with high priority
- Number if arrived packets with low priority
- Number if dropped packets with high priority
- Number if dropped packets with low priority

In order to perform plots the data should be collected manually from each of the simulation.